Contract No. F33615-88-C-3612
Report No. NAWCADWAR-92085-60

GUIDELINES FOR ADAPTIVE AID DESIGN: A REVIEW OF THE LITERATURE

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JULY 1992

INTERIM REPORT

Prepared for
Air Vehicle and Crew Systems Technology Department (Code 6021)
NAVAL AIR WARFARE CENTER - AIRCRAFT DIVISION WARMINSTER
P.O. Box 5152
Warminster, PA 18974-0591

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LEVEL III Manager

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1992

3. REPORT TYPE AND DATES COVERED
Interim

4. TITLE AND SUBTITLE
GUIDELINES FOR ADAPTIVE AID DESIGN: A REVIEW OF THE LITERATURE

5. FUNDING NUMBERS
C: F33615-88-C-3612
PR: 3612-20

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SEARCH TECHNOLOGY, INC.
4725 Peachtree Corners Circle, Suite 200
Norcross, GA 30092-2553

8. PERFORMING ORGANIZATION REPORT NUMBER
STI-TR-9103-001

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Vehicle and Crew Systems Technology Department
(Code 6021)
NAVAL AIR WARFARE CENTER-AIRCRAFT DIVISION WARMINSTER
P. O. Box 5152
Warminster, PA 18974-0591

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NAWCADWAR-92085-60

11. SUPPLEMENTARY NOTES
NAWCADWAR POC: Jeffrey G. Morrison (6021)
Note: This draft is a report subject to revision; Contracted through U.S. Air Force Wright Patterson A.F.B. Contract # F33615-88-C-3612

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A literature review focusing on the identification of useful engineering design guidelines for adaptive aiding systems was conducted. Approximately 40 articles were reviewed, and over 140 design guidelines were extracted. Sources for the guidelines included concept development, empirical investigations, or analysis or fielded systems, and literature reviews in adaptive aiding technology. A two-dimentional taxonomic structure was developed and used to categorize the guidelines. The first dimension of the taxonomy is based on Rouse's (1988) framework for adaptive aid design. The second dimension focuses on the design implication of each of the identified guidelines. This structure allows for efficient categorization of the information and assists in showing where research results exist to help the designer of adaptive aiding systems. The guidelines are presented with rationale for each guideline included. The guidelines and supporting material in each cell of the taxonomy are analyzed for usefulness. Recommended areas of future research and analysis of the current research status in adaptive aiding is discussed.

14. SUBJECT TERMS
adaptive aiding, adaptive automation, human performance in adaptive automation, design of automated systems, aircraft autom

15. NUMBER OF PAGES
97

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Contract No. F33615-88-C-3612
Report No. NAWCADWAR-92085-60

STI-TR-9103-001

Guidelines for Adaptive Aid Design:

A Review of the Literature

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July 1992

Report submitted to the Naval Air Development Center under Task number: 3612-20, Prime Contract: F33615-88-C-3612 to Midwest Systems Research (Mr. Jeffrey G. Morrison, Technical Monitor). This is a draft report subject to revision. The views presented in this paper are those of the authors. Comments on this report may be forwarded to Robert Andes, Search Technology, Inc. at the above address.

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Abstract

A literature review focusing on the identification of useful engineering design guidelines for adaptive aiding systems was conducted. Approximately 40 articles were reviewed, and over 140 design guidelines were extracted. Sources for the guidelines included concept development, empirical investigations, or analysis of fielded systems, and literature reviews in adaptive aiding technology. A two-dimensional taxonomic structure was developed and used to categorize the guidelines. The first dimension of the taxonomy is based on Rouse's (1988) framework for adaptive aid design. The second dimension focuses on the design implication of each of the identified guidelines. This structure allows for efficient categorization of the information and assists in showing where research results exist to help the designer of adaptive aiding systems. The guidelines are presented with rationale for each guideline included. The guidelines and supporting material in each cell of the taxonomy are analyzed for usefulness. Recommended areas of future research and analysis of the current research status in adaptive aiding is discussed.

1.0 Introduction

The complexity of modern engineering systems (e.g., tactical aircraft, spacecraft, and process control systems) and the tasks that operators must perform within these systems have led to a boom of automation technologies to assist the operator in dealing with these emerging complexities. The shortcoming of most of these technologies is that although they allow higher performance on specific tasks, they introduce systems complexity problems of their own. Often, instead of reducing operator workload and increasing system performance through the use of automation technology, the automation only serves to *increase* workload on the operator and *decrease* situation awareness.

Originally, function aiding (e.g., Fitts, 1951) approaches were used by system designers as the automation philosophy. However, researchers and designers alike have since realized that the demands of highly automated modern systems (e.g., tactical aircraft) on the operator vary greatly over time and task loading. Often these systems demand an inordinate amount of operator attention. What is needed is a technology that integrates the automated functions and considers the operator's demands in a dynamic fashion. In other words, the automation must be flexible to handle manifold performance demands and be responsive to both the changing needs of the system as well as the human operator.

One concept introduced to mitigate the effects of increasing automation in systems is adaptive aiding (also referred to as "adaptive automation" and "adaptive function allocation"). Adaptive aiding is a systems automation philosophy that proposes the use of automation to assist the operator when system performance is likely to degrade past the point of acceptability at some point in the near future (Rouse and Rouse, 1983). The viability of adaptive aiding for system control has been discussed (Rouse, 1988) and demonstrated (Andes, 1987; Lind, 1989) in recent endeavors.

An increasing number of automated systems are being introduced into the aerospace and process control domains. To provide the optimal dynamic function aiding and human-aid interaction characteristics, a wide breadth of applicable human performance and systems design literature must be considered by the designer. A large base of research results, conceptual

development, and lessons learned contribute to the necessary knowledge for state of the art aid design.

Research in adaptive aiding has been accumulating over the past two decades. Much of this work includes conceptual development and empirical investigation in limited experimental domains. However, a substantial amount of this research is the post hoc evaluation of implemented systems or design methods. Inherent to this work are guidelines and suggestions that would be applicable to the design of future aiding systems. These guidelines are not often readily accessible to the designer because they are embedded within technical reports.

Rouse (1988) has compiled a number of relevant principles for adaptive aiding design in a review of the current state of the art in adaptive aiding technology. That collection, however, represents only a small sampling of the potential guidelines that would be useful for designers of adaptive aiding systems.

The current literature review was performed for several reasons. The primary effort was to assess the sophistication of design guidelines for adaptive aiding systems. Other reasons were to determine the usefulness of these guidelines and to assess the level of empirical support for the application of these guidelines to system design. The ultimate goal was to determine the directions for research that would be most appropriate given the current state of adaptive aiding system design. To this end, this document includes a review of those sources believed to be the most representative reference materials used in the design of aiding systems. This document is an important step in the production of a comprehensive set of engineering guidelines for designers.

This document is organized into six sections. After the introduction, Section 2 defines the scope and application of the guidelines presented throughout the document. Sources from several scientific domains (i.e., human performance literature, automated systems design, human-computer interaction studies, etc.) were consulted for the production of design guidelines. Core design guidelines were extracted from the references included in this paper, justified where appropriate, and categorized in a design-oriented taxonomy.

Section 3 explains the taxonomy developed for guideline organization. The taxonomy was produced to highlight the type of research that has been conducted, to organize the available design knowledge, and to identify where more work needs to be done.

Section 4 presents the guidelines arranged in the taxonomy according to supporting rationale. Each subsection presents a group of guidelines and discusses them in relation to the corresponding design issue. A rationale for each guideline is supplied as necessary, and implications for system design are addressed.

The summary and discussion in Section 5 analyzes the guideline groups in terms of sufficiency for design. Additionally, significant but lacking design information is identified, and suggestions for obtaining requisite design knowledge are proposed.

Section 6, the final section of this review, discusses the current state of the art in aiding design. This section addresses what types of research should be directed to provide the knowledge that will empower the designer to produce optimal adaptive aiding systems.

2.0 Scope and application of this document

Literature relevant to the design, implementation, and evaluation of adaptive aiding systems spans several areas of computer science, systems engineering, and human factors psychology. The current review is an initial step in the production of a comprehensive set of engineering guidelines for aid design. As such, approximately 40 articles covering the aforementioned areas have been reviewed. One hundred forty-two design guidelines have been extracted; these are enumerated and discussed in this document.

The articles reviewed in preparation of this document represent the prime reference material used by adaptive aiding designers at Search Technology. This material is viewed similarly in the government and aerospace design communities. System implementations and evaluations, and interaction and communication studies were reviewed to establish a range of guidelines that address the numerous issues faced by designers of aiding systems. The guidelines extracted from these sources discuss conceptual approaches to aiding in terms of system design and user-aid interaction characteristics. The review was not exhaustive, but it covers several areas of concern.

There are two primary approaches to operator aiding: adaptive aiding (Rouse and Rouse, 1983), and function aiding (Fitts, 1951; Lind, 1989; Krobusek et al. 1985). Both approaches are considered in this review, since the

designer must decide which approach he will take early in the systems requirements process. Note that we cannot determine the correct philosophy: The design context may dictate what level of automation flexibility is appropriate. Further, system requirements often determine whether the system will be task-centered (i.e., function aiding) or human-requirements centered (i.e., adaptive aiding) (see Andes and Rouse, 1991 for an in-depth discussion of this issue).

It is important to mention that the current review is not merely a repeat of Rouse's 1988 *Human Factors* article "Adaptive aiding for human/computer control." The current paper attempts to integrate Rouse's summarized material with information sources of a more applied genre. However, for organizational purposes, this review does rely on Rouse's Framework for Design (originally proposed in the 1988 review article).

The framework for design proposes six fundamental aiding design questions for the designer and suggests several possible answers to those questions. This review uses Rouse's framework as one dimension of an organizational taxonomy for design guidelines (this approach is quite rational when viewed from the designer's perspective). For example, each of the questions must be addressed to ensure that the design is the best possible for the current application. Further, by supplying guidelines for each of the questions, we facilitate the design process by allowing the designer to use the experience of others, even if the current application does not closely resemble the reference context. The second dimension of the taxonomy considers implications of the guidelines on the design process. The framework and taxonomy are reviewed in Section 3.

We have attempted to provide as much specific information as possible in each of the guidelines. It is a relatively simple matter to produce a high level guideline that provides little utility to an applied designer. The more difficult task is to extract useful design information from the literature, represent it in terms that applications engineers can understand, and indicate the domain of applicability for the guidelines that result. We hope that this document provides a useful start on that process.

Although this review is written from the psychological perspective of human-aid interaction, it addresses the engineering design community foremost. The reader should note that most of the guidelines have 1 supporting empirical investigation **at best**, and some of that supporting material may be of

a speculative nature. In addition, the generalizability of some of the guidelines is questionable, but worth mention. Nonetheless, the applicable material and supporting literature content of the guideline are covered as completely as possible. Relevant material will be presented to support this viewpoint.

3.0 Adaptive Aiding Design Guideline Taxonomy

Engineering design guidelines must address specific issues to be useful to the designer. As stated earlier, the present review has produced 142 individual adaptive aiding design guidelines from various sources. A serial listing of these guidelines does not provide much utility. In fact, such an arrangement may actually reduce utility and confuse a designer who is attempting to apply relevant information to the design problem at hand.

One major requirement for any classification scheme chosen is that it support the engineering design perspective. Another requirement is that it cover all issues faced during the engineering design process. Further, this classification scheme should support expansion as research in the field of adaptive aiding progresses.

Several approaches to guideline classification were identified and evaluated for the current review. The initial guideline organization process involved partitioning the guidelines into two types of design principles: Principles of adaptation and principles of interaction. Principles of adaptation prescribe when and how adaptation occurs. Alternatively, principles of interaction relate to operator acceptance of the aiding. This distinction was initially applied to the list of guidelines, however, it became apparent that the resulting principles-based categorization was insufficient in characterizing the robustness of the guidelines.

Since the aiding system design community is the intended audience of the guidelines in this document, the Framework for Design proposed by Rouse (1988) was chosen as the taxonomy for organizing the guidelines. Within this framework, a structured set of conceptual design issues are systematically addressed. Though context specificity is not directly addressed, the framework provides the aid designer with an outline of the range of possible design alternatives and information that designers may use in choosing among them. The questions posed within Rouse's framework for design are discussed below.

What is adapted to? - The designer of the aiding system must determine which system entities are adapted and which are left in a fixed state. Either the operator, the system, or the aid may adapt in a given situation. There are also several levels within each entity that may be adapted. For example, a class of operator, a particular operator, or a particular operator in a specific situation may be adapted to accommodate environmental circumstances and the present task. Furthermore, the aid may adapt to the user and/or the task.

Who does the adapting? - The designer, the aid, or the system operators may invoke adaptation in a given situation. The aid should initiate adaptation if the system's definition of adaptation must be refined, or if operators are unlikely to perceive the need for adaptation. Additionally, the entity that invokes adaptation must interact with either static or dynamic adaptation within the system. Static methods of adaptation are determined by design specifications before implementation, and do not change during system use. Dynamic adaptation is based on changeable environmental, system, or operator conditions, and is typically associated with the image of adaptive aiding.

When does adaptation occur? - Adaptation may occur off-line (prior to system operation) or on-line (according to changing system demands). Additionally, an aid may determine that a pilot needs assistance, but will wait until a proper time to perform the aiding. Adaptive aiding should be invoked whenever pilot workload and performance demands change.

What methods of adaptation apply? - There are three primary methods of adaptation within adaptive aiding. *Transformation* involves changing a task to make performance of that task easier for the operator. *Partitioning* allows the operator to share performance of particiular tasks with the aiding system. *Allocation* is the the most common and the easiest type of aid to implement, where the aid either performs a task itself or allocates that task to the operator.

How is adaptation done? - Adaptation may be approached by measurement of operator or system performance, or by modeling operator resources, intentions, or system performance. These methods determine aiding needs within a system by addressing how inputs affect making the decision to aid.

What is the nature of aid-operator communication? - This addresses the information exchanged between operator and aid about the effects of adaptation. Explicit communication provides ample information exchange, but has high interface and interaction costs. These costs include demands on the pilot's time and cognitive

and attentional resources. Implicit communication does not impose a high cost, but may be ambiguous and result in communication error.

A thorough and accurate classification, however, required the inclusion of a second taxonomic dimension: implications of the guidelines on system implementation. This second dimension enabled us to classify guidelines in terms of their influence on system performance, workload, user acceptance of the aid, and situation awareness. We have integrated the two dimensions (design issues and the effects of guidelines on system behavior) in a 6 x 4 matrix to obtain a 24-cell taxonomy for guideline categorization.

The resulting taxonomic arrangement for the guidelines contained within this review is depicted in Table 1. The six design questions compose the rows of the taxonomy, and the four ways in which guidelines may affect adaptive aiding systems compose the columns. In Section 4, Adaptive Aiding Design Guidelines, we present the guidelines within the taxonomy and discuss the possible implications of the guidelines on system design and behavior. We have assigned a unique tag to each guideline to help the reader understand how the guidelines fit into the taxonomy. This tag has four parts: the section number (4; Section 4 contains all guidelines), a row number (1 through 6, corresponding to the six design questions), a column number (1 through 4, corresponding to the four effects of implemented guidelines on the aiding system), and a lower case letter unique to each guideline in a given cell of the taxonomy. For example, guideline 4.3.2.a is discussed in terms of the "When does adaptation occur?" design issue (row 3 of the taxonomy) and the implication of this guideline on workload (column 2 of the taxonomy). In other words, this guideline addresses how the timing of adaptation affects workload within a system. Finally, the "a" signifies that this guideline is the first discussed in this particular cell of the taxonomy.

DESIGN FRAMEWORK QUESTION	PERFORMANCE	WORKLOAD	USER ACCEPTANCE	SITUATION ASSESSMENT
What is adapted to?	4.1.1	4.1.2	4.1.3	4.1.4
Who does the adapting?	4.2.1	4.2.2	4.2.3	4.2.4
When does the adaptation occur?	4.3.1	4.3.2	4.3.3	4.3.4
What methods of adaptation apply?	4.4.1	4.4.2	4.4.3	4.4.4
How is adaptation done?	4.5.1	4.5.2	4.5.3	4.5.4
What is the nature of operator-aid communication?	4.6.1	4.6.2	4.6.3	4.6.4

Table 1 - Design Guideline Classification Taxonomy

4.0 Adaptive aiding design guidelines

The guidelines extracted during the review process are presented in this section, categorized according to the taxonomy introduced in Section 3. There are six major section headings, each of which corresponds to one of the six framework for design questions. These six sections are further divided into four subsections that address the design implications for the guidelines. The subsections discuss the effects of guidelines on the resulting design in terms of performance, workload, operator acceptance, and the ability to maintain situational awareness. The guidelines, rationale for the guidelines, and relationships between guidelines are then discussed with supporting information included where needed.

4.1 Guidelines for "What is Adapted To?"

This section addresses the object of adaptation. In an adaptive aiding scenario, the task may be adapted to make it easier for the human to perform. Alternatively the human may be adapted through training to perform the task more proficiently. The effects of beneficial adaptation will be manifested as improvements in system performance, achievement of optimal levels of operator workload,

increases in operator acceptability of an aiding system, and increases in the ability of an operator to achieve situation awareness.

4.1.1 Implications on Performance

The operator or the aiding system may be adapted in any aiding situation. Therefore, the performance of a system is largely affected by the actions of the operator or the aid in response to adaptation. This implies that design decisions require the consideration of the effects of adaptation on system performance. This section presents guidelines that address how adaptation of an agent affects system performance. In particular, it discusses the effects of the choice of interface format, development of aiding system knowledge structures, adaptation to user capabilities, allocation of tasks, and the process of aiding on system performance output. The guidelines are enumerated below.

Guidelines

4.1.1.a The selected knowledge representation scheme for aid should be able to provide a framework for representing system task knowledge. One approach is using scripts, plans, and actions (Shank and Abelson, 1977). Another is to use state transition-action diagrams to affect system state through aiding (Andes, 1987).

Explanation: The manner in which operator knowledge and ability are represented during design of an aid may affect how well the implemented aid ultimately performs. During design it is important to consider the tasks that are to be aided and context under which aiding will occur. According to Andes (1987), the knowledge representation system within the aiding system should account for knowledge that operators use during task execution. The choice of knowledge representation scheme depends on aiding context, the number of decisions required in a procedure, and the level of control achievable by the aid in the system.

Empirical Support:

4.1.1.b Use adaptive interfaces to support: metaphoric consistency, short-term memory support, maintenance of user context, context customization, learning acceleration, and error recognition (Norcio and Stanley, 1989).

Explanation: This guideline addresses the conceptual stages of adaptive interface design. For example, when a pilot is learning to incorporate performance of a given task with other tasks, the information in the interface should be explicit. As the pilot becomes proficient in incorporating all tasks, the interface should be less explicit to avoid providing the pilot with information that he no longer needs to perform those tasks. This guideline is in accord with good design of display interfaces for computer software in general, and would be well-suited to the design of adaptive aiding systems. An illustrative example of guidelines 4.1.1.a and 4.1.1.b can be found in Rouse, Geddes, and Curry (1987).

Empirical Support:

4.1.1.c Designers are interested in producing consistent behavior of aiding behavior in normal vs. novel situations (Andes and Rouse, 1991).

Explanation: Andes and Rouse have found that designers of aiding systems are interested in system reliability in both normal and novel situations. Although one goal of designers is to build systems that successfully aid operators in highly likely situations, designing systems with expandable functionality is an additional goal of significant importance. Thus, designers are interested in knowing how an aid will perform in situations outside of the intended functional envelope.

Empirical Support: The study by Andes and Rouse (1991) addressed what kind of information aiding designers value in the development of aiding specifications. Statistical analyses of designers' preferences showed that designers were interested in reliability of the aid on tasks other than those for which the aid was originally designed.

4.1.1.d Use adaptive interfaces to support: mixed dialogue initiative, vigilance support, navigational support, progressive disclosure, and regulation of control and display surfaces (Norcio and Stanley, 1989).

Explanation: Note that these features are related to changes in the appearance of the system to the user over time. By including these features within an aiding system, the designer insures that the system adapts to user's needs. Although this and the next guideline were originally designed for computer interfaces, they address some of the same issues present in the design in display interfaces for adaptive aiding systems.

Empirical Support:

4.1.1.e The designer of decision support systems must derive the following from decision makers in the beginning stages: list of user objectives and objectives hierarchy, list of alternative decisions, and a list of outcomes for each alternative (Sage and White, 1984).

Explanation: Knowledge representation should consider the operator information requirements and purpose of the aid as well. Designers of decision support systems must derive information from operators in the initial stages of design. This information should include a list of user objectives and an objectives hierarchy, a list of alternative decisions, and a list of possible outcomes for each alternative. Such an analysis of the requirements of decision support systems enables the designer to evaluate alternative plans and decisions efficiently. Further, it allows the designer to discover and utilize existing dominance patterns among alternatives.

Empirical Support: Weisbrod, Davis and Freedy (1977) provide an empirical analysis of dynamic decision processes. They have determined that direct judgement techniques, measurement of user utility values, and dynamic utility estimation are useful ways to estimate and update the decision maker's utility functions for decisions. Their work is discussed in more detail in Section 4.1.3.

4.1.1.f Use flexible automation as a means for increasing the proficiency of novice users and for preventing frustration that may occur with overly complex systems (Norcio and Stanley, 1989).

Explanation: Adaptive aiding is useful in increasing performance of operators with different skills. Variable adaptation should be used in adaptive aiding systems to increase the proficiency of the novice user, and to prevent frustration that may otherwise occur with the use of complex systems.

Empirical Support: Although this design guideline is commonly held as true, it is in need of validation.

4.1.1.g The long-term impact of automation on pilot skills should be considered early in the design process. Effective training programs must also be designed to maximize the pilot's contribution to mission effectiveness (Parasuraman, Bahri, Deaton, Morrison and Barnes, 1990).

Explanation: This implies that in highly automated systems, pilot skills may degrade if they are not practiced. The long-term impact of automation should be considered early in design since it is easier to include embedded training in the system during the design process. Further, the purpose of effective system-use training programs should be to maximize the pilot's contribution to mission effectiveness.

Empirical Support: This guideline is widely accepted in the operational community and is probably not necessary to validate.

4.1.1.h Training programs in adaptive aiding should stress operator-aid interaction skills and cognitive/problem solving skills rather than psychomotor skills (Parasuraman et al. 1990).

Explanation: Inadequate training may lead to widespread automation-induced pilot skill decrements. Furthermore, automation necessitates a shift from psychomotor skills to cognitive and problem solving skills.

Training must augment cognitive and problem solving skills so that pilots maintain the ability to handle complex problem situations when automation fails or when problem dimensions are out of the aid's range.

Empirical Support:

4.1.1.i Allocation of tasks to man or machine depends on the state of the system and the state of the world (Boys, 1990). Within each system function, different levels of system autonomy (LOA) are possible.

Explanation: Task allocation (the "what" that is adapted to) has been analyzed from a variety of directions. Boys claims that optimal allocation of tasks to man or machine depends on the state of the system and the state of the world. The way tasks are prioritized is affected by contextual factors which change over time. Another factor that affects task allocation is the level of aiding autonomy assigned to a system by the designer or the operator. A system with total autonomy will assume performance of all tasks. Alternatively, a system with no autonomy assumes the operator will perform all tasks unless the operator off-loads some of them to the system. The levels of autonomy (LOA) concept has been developed by Krobusek, Boys and Palko (1989), and is discussed in more detail in Section 4.4.1.

Empirical Support: See Krobusek, Boys and Palko (1989) for further support of this task allocation guideline.

4.1.1.j Beware of basing allocation decisions solely on computer aid abilities. Human's aptitudes, cognitive styles, and attitudes may affect behavior across situations (Morris, Rouse, Ward and Frey, 1984).

Explanation: Humans' abilities should be considered and used during allocation decisions because those abilities are a valuable resource to system control. It must be remembered though, that humans' aptitudes, cognitive styles, and attitudes may affect their behavior across situations, and that behavior as such may not be totally reliable. The Fitts' type list of human abilities that would result from basing allocation decisions on computer abilities would not account for individual differences between

humans, however. Such a list would therefore not optimize task allocation decisions.

Empirical Support:

4.1.1.k A balance between task difficulty and automation must be found so that the human is performing at an optimal level of task stimulation; the task should be neither too difficult (overarousing) nor too easy (underarousing) (Morrison, Gluckman and Deaton, 1990).

Explanation: Humans perform best over a limited range of task stimulation. If the effort required is too high, the human may fail to do the task. If the effort required is too low, the human may suffer vigilance decrements.

Empirical Support: This conclusion relates to the work of Sen (1984), where the balance of information input to a human decision maker was analyzed empirically. Sen found that optimal human performance required a certain level of task difficulty, and automation of the remaining tasks.

4.1.1.l Beware of creating a passive, complacent operator through use of automation for routine tasks if the operator is responsible for intervention during system failure. Consider involving the operator in these tasks as an active agent and using embedded training (Parasuraman et al. 1990).

Explanation: Since a passive operator's skills are susceptible to complacency and boredom, the operator may not be capable of taking-over tasks if the system fails. Parasuraman et al. suggest that designing embedded training into the system will keep the operator actively involved in system activities.

Empirical Support: Several studies have found that performance of boring tasks decreases with increased performance time. This guideline is well-supported by human performance literature.

4.1.1.m Users may adapt to the aid and/or the task depending on their functional models of the aid and their own level of expertise (Rouse, 1988).

Explanation: Designers must be able to determine how operators' conceptual models of aiding systems and their levels of expertise affect adaptation because humans adapt to everything.

Empirical Support:

4.1.1.n In multiple task situations, it is more desirable to aid a few tasks with emphasis on increased performance than to aid the prioritization of all tasks to be completed by the operator (Derrick, 1988).

Explanation: Derrick found that human and system performance was better when a few tasks were aided than when the human performed tasks according to schedule and task priorities.

Empirical Support: This was supported by the findings of Wickens and Yeh (1983), where subjective effort ratings focused more on processing requirements than performance outcomes. Basically, humans are more concerned with what they have to do rather than how well they do it. In other words, humans are good at prioritization -- task performance support will yield better results than support of task scheduling.

4.1.1.o Attempt to spread operator resource demands over the largest number of resource structures in dual-task environments. This is consistent with Multiple Resource Theory and will yield smaller performance decrements than concentrating processing demands on a minimal number of resources (Derrick, 1988).

Explanation: In accord with Multiple Resource Theory (MRT), Derrick suggests that in dual-task environments, operator resource demands are spread over as many human processing resource structures as possible. This procedure minimizes human performance decrements because it prevents the overload of one particular processing resource. The visual system or the auditory system are examples of processing resources.

Empirical Support: In experiments, Derrick found the greatest performance decrements in dual-task pairs where processing demands were spread over a minimal number of resource structures. In order to minimize performance decrements then, demands on an operator's resources should be distributed among the largest number of resources.

4.1.1.p System response time to operator action must not degrade system effectiveness. Changes in response time should be considered following changes in task allocation responsibility, and to identify the time required to reconfigure the system (Krobusek, Boys and Palko, 1989).

Explanation: Krobusek, Boys and Palko (1989) discuss the general requirements for successful aiding system performance. Of the most important requirements is minimizing system response time. This may be difficult to achieve, however, because changes in task allocation may increase system response time in two ways. First, the pilot must spend some amount of time reconfiguring task allocations, and second, any reallocation may affect the ability of the system to respond promptly. Designers should consider the effects of system response time on system effectiveness during the design process. In addition, Andes (1990) and Morrison, Gluckman, and Deaton (1990) have discussed the criticality of maintaining response time with regard to hardware and intervention methods.

Empirical Support:

4.1.1.q Systems that relax control requirements improve both control and subsystem performance, but systems (e.g., on required control performance) that relax subsystem requirements improve only subsystem performance. Consider this result when constructing the top-level design for the system (Chu and Rouse, 1979).

Explanation: One factor that should be considered early in the design process is the system capacity to relax control requirements. However, systems that relax subsystem requirements improve only subsystem

performance; control performance is not improved. This was attributed to the fact that control tasks have priority over subsystem tasks, and that control task inefficiency is likely to affect subsystem task performance.

Empirical support: The experiment performed by Chu and Rouse provides support for this guideline.

4.1.2 Implications on Workload

Pilot workload is affected by changes in the status of current tasks, and by the introduction or removal of other tasks. If the pilot is the entity that adapts in a given situation, he may experience a temporary or long-term increase in workload. The pilot must learn to manipulate the system to his benefit and to incorporate new external information into the performance of current tasks. If alternatively, the aid adapts, the pilot is free to proceed with current tasks, and may not even be aware of the aid's activity. In situations where the aid adapts to either the pilot's actions or the task, pilot workload is unlikely to increase. Guidelines having implications for pilot workload are enumerated below.

Guidelines

4.1.2.a Pilot workload should be optimized rather than simply minimized in adaptive automation systems (Parasuraman et al. 1990).

Explanation: Apparently, operators are unable to remain focused on tasks that involve extremely low levels of workload, and are consequently unable to perform these tasks well. An optimal level of workload should be assigned to the operator to insure his active participation in system functioning. Methods of workload optimization will be specifically addressed in section 4.5.2.

Empirical Support: This guideline has been reflected in the results of several studies conducted in the fields of vigilance and automation performance deficit. It has been shown that both extremely high and low workload situations degrade task performance.

4.1.2.b At low rates of information input to the operator, mean decision time (time required to decide what output corresponds with the input) is a linear function of information input (Sen, 1984).

Explanation: The work of Sen has provided insight into the differences between the human decision maker and the mathematically ideal decision maker. His work also addresses how these differences influence the distribution of workload in decision support environments. This guideline states that for low information input rates, the higher the input rate, the longer it takes to make a response decision. Furthermore, the relationship between input rate and decision time is linear.

Empirical Support: Sen's work provides direct support for this guideline.

4.1.2.c At high rates of information input to the operator, information overload occurs, and the linear function of information input breaks down (Sen, 1984).

Explanation: The typical human decision maker experiences information overload at high information input rates. This is evidenced by the breakdown of the linear function between information input rate and information processing time; the human is no longer able to keep decision-making pace with the rate of input.

Empirical Support: The functions produced by Sen are useful in modeling information inputs for human-aid interaction.

4.1.2.d Input to a decision maker can be partitioned into groups depending on its characteristics. When input approaches overload, the decision maker ignores certain characteristics and prioritizes the input with regard to the most important characteristics (Sen, 1984).

Explanation: This behavior helps reduce the possibility of overload because it minimizes the amount of input that the decision maker must account for.

Empirical Support: Research by Miller (1969) supports this guideline by showing that the number of decision maker errors increases significantly during input overload situations. The decision maker is unable to consider all the information required for making correct decisions.

4.1.2.e Random omission of information pertinent to the decision process occurs when the decision maker simply does not make a decision when he is given certain conditions. This occurs with low frequency at low and medium information input rates, but with significantly high frequency at high input rates (Sen, 1984).

Explanation: Since the decision maker cannot account for all information provided to him during increasingly high input rates, he may omit certain pieces of information from consideration on a random basis. Errors that result from this type of information processing strategy are called random omission errors. These errors occur infrequently at low and medium information input rates. However, they occur with much greater frequency at high information input rates.

Empirical Support: Miller's (1969) work provides support for this guideline.

4.1.2.f In incomplete decision responses under high workload, the decision maker specifies input within a set of bounds and takes a partial course of action. This is a conscious overload avoidance strategy in which the decision maker uses only part of relevant input available; the decision maker exhibits error behavior in order to avoid overload (Sen, 1984).

Explanation: Incomplete decision responses occur when decision makers consider only the information that has particular characteristics, or falls within a certain range of topics. The decision maker makes response decisions after considering only part of the input, and therefore makes only partial responses. Like random error behavior, incomplete decision response is a conscious overload avoidance strategy that occurs at medium and high information input rates.

Empirical Support: A clear explanation for this phenomenon does not exist.

4.1.2.g Try to preserve "cognitive unity" when transforming a task. Cognitive unity refers to the operator's perception that the transformed task is the same as the original task (Andes, 1990).

Explanation: This guideline applies directly to the design of adaptive aiding systems. When an aided task supports cognitive unity, the operator perceives the transformed task to be functionally the same as the original task. Andes promotes the preservation of cognitive unity to make aided tasks easier to perform.

Empirical Support: Although transformation aiding implies that the two tasks are the same, the human operator may actually perceive two different tasks. This is expected to lead to an increase in workload, but such an effect has not been empirically evaluated.

4.1.2.h Pilots can be trained to reconfigure task allocation dynamically using levels of automation (LOA) approach. Task allocation should be based on sensory, cognitive, and behavioral capabilities of the pilot population (Krobusek et al. 1989).

Explanation: Regardless of automation approach, researchers in the adaptive aiding field commonly espouse this guideline. Task allocation should be based on sensory, cognitive, and behavioral capabilities of the pilot population in order to minimize the negative effects of workload on operator performance. In addition, pilots should be trained to account for these capabilities since they may be responsible for changing task allocation configurations during adaptation.

Empirical Support:

4.1.2.i In a multiple alternative decision support environment, use decision analysis to support ranking of alternative decisions based on the

dominance structure of the decision maker's prioritized alternatives (Sage and White, 1984).

Explanation: Sage and White suggest that designers use decision analysis to enable ranking of alternative decisions to support multiple alternative decision making. This ranking should be based on the dominance structure of the decision maker's prioritized alternatives. The purpose of this analysis is to decrease interaction time and increase overall system efficiency for each individual operator. In their paper, Sage and White provide explicit algorithms for performing such analyses.

Empirical Support:

4.1.2.j Apply aiding during air-to-air combat with mission-phase tailoring. Mission-phase tailoring defines specific tasks (functions) that are automated as a function of the mission phase (i.e., intercept, within visual range combat maneuvering, weapons delivery, disengagement) (e.g., Lind, 1989).

Explanation: In air-to-air combat, workload may be minimized by aiding through mission-phase tailoring. This type of aid tailoring defines specific tasks that are automated as a function of the mission phase. Lind has found that introducing aiding in a mission-phase tailored manner fosters user acceptance of the aid and minimizes workload because the aided tasks are predefined and the pilot is aware of his task responsibilities at all times.

Empirical Support:

4.1.3 Implications on Operator Acceptance

Operator acceptance of the aid is critical to the successful incorporation of adaptive aiding systems in the cockpit. If user acceptance is considered in decisions of what is adapted to in the system, the relative abilities of different users must also be considered. Investigators have begun to develop guidelines in order to

achieve user acceptance of aiding, however not all of these guidelines have been empirically validated.

Guidelines

4.1.3.a Designers are interested in information about the appropriate motivations for different types of aiding (Andes and Rouse, 1991).

Explanation: Andes and Rouse have determined that the designer's approach to the acceptance issue is to consider information about the appropriate motivations for different types of aiding. Designers promote aid acceptance by deciding what type of aiding would be desirable to the operator in a particular context.

Empirical Support: Andes and Rouse (1991) provides support for this guideline.

4.1.3.b Two levels of operator preference information necessary for aid tailoring are: population preferences and individual operator preferences (Andes, 1990).

Explanation: Operator acceptance of an aid depends on whether operator preferences are accounted for during design. The appropriate mix of population preferences and individual operator preferences that results in optimal aid tailoring and user acceptance is not yet known. It is likely that the aid-operator interaction will provide information relating the the necessary level of tailoring.

Empirical Support:

4.1.3.c Incorporate models within the aid that allow predictions of the <u>relative</u> abilities of users and the aid to perform the task in particular situations (Rouse, 1988).

Explanation: Rouse has suggested that operator acceptance would be fostered if the aid were capable of predicting whether the user or the aid would better perform a task in a given situation. Furthermore, aiding strategies that are based on user populations are likely to be accepted because the relative abilities of users and aids are accounted for. Thus, operator ability provides the basis for task allocation. The incorporation of predictive performance models within the aid are necessary to determine whether the aid or the operator will better perform a task.

Empirical Support: Lehner et al. (1987) and Morris and Rouse (1986) have also addressed the issue of operator acceptance in the context of task allocation.

4.1.3.d Dynamic adaptation of the interface to the user may be attained by utilizing information provided to the system through user interactions with it in a specific context (Norcio and Stanley, 1989).

Explanation: Norcio and Stanley have found that user interactions provide information that can be used by the system to allow dynamic adaptation of the interface to the user. These interactions should be paired with the contexts in which they were performed if they are to be properly used as the basis for adaptation. The dynamic adaptation approach is similar to using operator intent as the basis for adaptation, and is believed to promote operator acceptance of an aid. Rouse, Geddes and Curry (1987) provide an analogous approach to supporting user acceptance of aiding in complex systems by determining user intent.

Empirical Support:

4.1.3.e Estimating user utility values: Use direct judgement technique to get a value for each decision outcome. Combine these single utilities linearly to produce the decision maker's utilities for complex decisions (Weisbrod et al. 1977).

Explanation: Dynamic parameter estimation is a viable method of attaining operator acceptance of decision support aids. Weisbrod, Davis and

Freedy (1977) have evaluated this approach with an implemented decision aiding tool, ADDAM, and have developed three guidelines which may apply well to adaptive aiding systems (guidelines 4.1.3.e to 4.1.3.g). This guideline suggests using direct judgement to estimate user utilities for specific decision outcomes. The single utilities can be combined linearly to produce utilities for complex decisions. Both single and complex utility values can be used to determine the best decision support system output for a for each user.

Empirical Support: The Weisbrod et al. study supports this guideline by showing improved operator performance with this type of decision aiding. Madni (1988) provides another example of the dynamic parameter estimation technique.

4.1.3.f Estimate user utility values for decision output by inference from behavior in a simple gamble. The decision maker responds to simple gambles with monetary rewards. The choices form a database from which utility values are inferred dynamically (Weisbrod et al. 1977).

Explanation: User utility values can be inferred by pooling a user's behavior in several simple gamble situations. Utilities may thus be inferred dynamically from these user behaviors. The utility values can then be used to determine the best decision support output in differing decision contexts. This technique was shown to be highly useful during dynamic adaptive aiding situations.

Empirical Support: see 4.1.3.e.

4.1.3.g Use Dynamic utility estimation to estimate and update the decision maker's utility functions for decisions by observing alternative decision preference in context and dynamically reconstructing utility functions based on changing decision maker behavior (Weisbrod et al. 1977).

Explanation: Dynamic utility estimation in decision support systems may foster user acceptance because the decision maker's utility functions are continually estimated and updated. The user does not get the impression

that the system is basing its aid in utility estimations that are no longer accurate. Dynamic estimation can be accomplished in aiding systems that record alternative decision preferences in specific contexts and continually reconstruct utility functions based on changing decision maker behavior.

Empirical Support: see 4.1.3.e.

4.1.3.h Decision making systems using dynamic utility estimation techniques foster user acceptance because operators feel that the aiding is based on their own values, giving them a high degree of apparent control (Weisbrod et al. 1977).

Explanation: When decision support is an important part of the adaptive aid, the designer can embed dynamic utility estimation in the system to optimize decision support output. If the aid is based on changing user preference structures, the user is more likely to approve of the aid. This is related to aiding tailorability, which is an important issue in the adaptive aiding field.

Empirical Support:

4.1.4 Implications on Situation Assessment

Whether the operator, the aid, or the task is adapted in a given situation affects the ability of either the operator or the aid to assess the current situation. If the operator is adapted, he may be unable to achieve situation assessment because he is engaged in adapting tasks. If the aid is adapted, the operator is free to consider information about the current situation, however, the aid may be unable to account for new information about the current status of the system. Further, if the task is adapted, the operator may be preoccupied with performing the new task and may not be able to effectively integrate new information. It is important to also consider research that has been conducted on situation assessment abilities of the aid and the operator in this section.

Guidelines

4.1.4.a Four domains of knowledge are necessary in any operator aiding system: knowledge of the current user, knowledge of interaction scheme, knowledge of problem task, and underlying operational knowledge (Norcio and Stanley, 1989).

Explanation: In their literature review, Norcio and Stanley concluded that the above four domains of knowledge are necessary in any operator aiding system. User knowledge includes users' cognitive limitations and strengths, perceptual weaknesses and strengths, problem solving strategies, attentional allocation, and mental models of the aiding system. Knowledge of the interaction scheme can be inferred from the interface format. Problem task knowledge can be inferred through task modeling based on the system's performance of the task, and goal detection and plan inference based on the user dialogue context and the environment. Finally, the underlying system knowledge can be achieved through optimizing the input and output within the boundaries of system's limits. Although knowledge requirements may not change for the user of a particular interface in a particular situation, they are likely to change for the aiding system throughout a pilot's mission. Such changing conditions should prompt the adaptive aiding system to continuously and dynamically assess which of the four types of information (user, interaction, problem task and system information) are available for analysis. Andes (1987) discusses these issues from the implementation perspective.

Empirical Support: This guideline was extracted from a literature review; the original sources provided the validation for each conclusion.

4.1.4.b The system must allow the pilot to efficiently adjust attentional resources within a pre-specified amount of time to allow him to intervene if the system fails. This is primarily an operator information requirements issue (Morrison, Gluckman and Deaton, 1990).

Explanation: Pilot situation assessment abilities must be supported by any aiding system. Further, the system must allow the pilot enough time to adjust his attention so that he can intervene efficiently before the system

fails completely. The operator, like the aid, requires certain information at particular points in time to maintain acceptable levels of system operation.

Empirical Support: Both Logan (1990) and Gluckman (1990) have noted that the time required is variable for operator adjustment to workload changes during system failure. This issue needs further investigation.

4.1.4.c The cost of attending to one subsystem and ignoring the others is a function of the changes in subsystem states that occur during the time that it is ignored (Greenstein and Revesman, 1986).

Explanation: An operator's ability to assess situations is affected by the degree to which he attends to some aiding subsystems and ignores others. Additionally, situation assessment ability is influenced by the number of changes that a occur in a subsystem while it is ignored. Since operators cannot directly observe system states, they must be estimated through system displays. In order to perform this estimation, the operator must focus on one subsystem and is therefore unable to monitor all active displays. The longer a given subsystem is ignored, the more it may change. Consequently, the cost incurred by ignoring that subsystem increases as well.

Empirical Support: More research is necessary to determine how inferences of subsystem states may be optimized through decision aiding.

4.1: Section Summary

This section discussed the implications of what is adapted in an aiding system based on different aspects of system performance. The guidelines emphasize the importance of adaptive interfaces, the use of appropriate knowledge representation schemes, operator decision support, and the consideration of pilot expertise and the aid's effects on the pilot in the design of aiding systems. These guidelines suggest that designers should: a) implement aiding systems to optimize pilot workload and task allocation throughout each mission, and b) allow operators to dynamically tailor the aid to personal preferences and abilities.

4.2 Guidelines for "Who Does the Adapting?"

Researchers have addressed the issue of whom is the appropriate agent of adaptation. In several research examples, the human operator adapts to the situation, particularly in the case of novel contexts. The designer must consider the inherent abilities of both operator and aid, and make decisions about who should initiate aiding accordingly.

The operator or the aid may use two types of adaptation for any situation in the environment. These are static and dynamic adaptation. Static adaptation implies that information is considered once, and then an adaptation decision is made. Dynamic adaptation implies that there is a continuing account of system status, and that the adaptation occurs with regard to changes in this information. Generally, in a given system, if the process of adaptation must be refined and/or changed and it is unlikely that the operator will perceive the need for change, then the aid is the appropriate agent of adaptation. Otherwise the operator should initiate adaptation.

4.2.1 Implications on Performance

In aiding systems, either the aid may be adapted to the operator, or the operator may be adapted to the aid. Undoubtedly, system performance will be affected depending on which agent is selected for adaptation. The goal of the designer is to determine how to which agent will best perform a given task based on contextual and predictive information.

Guidelines

4.2.1.a Task allocation default mode should be the human, with the option to delegate tasks to automation when he is unable to make allocation decisions within the time available (Morris and Rouse, 1985).

Explanation: This guideline suggests that, in order to optimize aiding system performance, the human operator allocate tasks unless he does not have enough time to make effective decisions. Three facts support this guideline. First, current technology does not permit automation of all existing types of system control. Second, coherence of the human's overall role in the system is promoted when the human makes allocation

decisions. Third, humans are more likely to accept this approach than others because it gives them a high degree of apparent system control.

Empirical Support: Morris and Rouse's (1985) study provides support for this guideline.

4.2.1.b Effective use of an aid requires that humans are able to determine when and how the aid should be used, and when it should not be used (Morris, Rouse, Ward, and Frey, 1985).

Explanation: If the operator knows when and how to use an aid, it is acceptable to allow him to be in charge of applying the aid. However, when the operator does not know when and how to use an aid, automated decision aiding should be invoked. This will allow optimization of system control and aiding application.

Empirical Support: The Morris et al. study supports this guideline. The operator control of aiding issue is also discussed by Morris, Rouse and Frey (1985), and Lehner et al. (1987).

4.2.1.c Availability of aiding in a system can affect performance positively even when the aid is not in use (Morris and Rouse, 1986).

Explanation: Morris and Rouse have shown that operator performance increases with the simple availability of an aiding system. This is true regardless of whether or not the aiding system is used. Thus, the operator's perception of being in control of the aiding system may have a critical effect on operator and system performance.

Empirical Support: The study provides support for this guideline.

4.2.1.d The costs associated with task automation may be slowed response to unexpected events while monitoring the automation (Parasuraman et al. 1990).

Explanation: When operators are required to change their interaction with a system from passive monitoring to active engagement, their responses are slower than if they had not been required to passively monitor the system. This shows that the degree of task automation can affect human operator performance as well as system performance. Furthermore, responses to unexpected events will be especially slowed, not only because operators have been monitoring system activity, but because they are not prepared for such events.

Empirical Support: Related to this guideline, Bortolussi and Vidulich (in press) have found that pilots prefer manual control over high priority tasks like weapon selection, weapon delivery, and flight control. During critical events, slowed responses to these tasks could jeopardize the mission.

4.2.1.e Tasks that are least likely to be voluntarily performed by the pilot (i.e., complex, difficult tasks) should be automated if possible (Morrison et al. 1990).

Explanation: In dynamic task allocation situations, tasks that pilots are least likely to perform should automatically be allocated to the aiding system. However, if the pilot does not want the aid to execute a given task (e.g., if the pilot is aware that a target is using a tactic not known to the aiding system), he should be able to regain control of that task. This suggests that both operator and system control of task allocation will help optimize system performance.

Empirical Support: This guideline is supported by the CAS1 study in the Morrison et al. paper.

4.2.1.f Dynamic allocation of tasks should be employed to insure that a given task is optimally assigned to the agent that is better able to perform that task. Dynamic allocation uses the system's resources more effectively than static allocation (as is the case in Fitts' list) (Krobusek et al. 1989).

Explanation: Task allocation is static when it is based on the functional abilities of the human operator or machine as determined by the Fitts List.

Static allocation does not account for changes in either humans' abilities or environmental conditions over time. Dynamic allocation is, however, based variable conditions and ensures that a given task is optimally assigned to the agent that is better able to perform that task at that point in time.

Empirical Support: Though widely accepted in the adaptive aiding domain, this guideline requires further support.

4.2.1.g Problem solving should be allocated to the agent that is likely to have the better solution to the problem. The implies that the decision maker must be able to discriminate situations on the basis of who (operator or aid) is more likely to be correct (Lehner et al. 1989).

Explanation: This guideline is similar to Guideline 4.2.1.f, but carries the additional implication that if tasks are dynamically allocated by the decision maker (the human operator), he must be able to tell whether he or the aid will provide the better problem solution. A point to consider here is that operator performance is better when the human feels in control of the system, even when the aid is not active (Morris and Rouse, 1986; Guideline 4.2.1.c). Therefore, system performance may be optimal when the human controls task allocation.

Empirical Support: The Lehner et al. study supports this guideline as does Morris and Rouse (1986).

4.2.1.h The amount of stimulus information classified per unit time depends on: size of stimulus class, experience level of the operator, speed/accuracy of operator, and the stimulus-response compatibility of the displays and controls (Barnes, 1981).

Explanation: The way information is displayed affects the ability of the human operator to classify that stimulus information and to perform tasks assigned to him. Interfaces that display aiding information should therefore be designed to optimize the speed with which an operator can

classify that information and subsequently make decisions. Barnes also provides guidelines for information display.

Empirical Support: This guideline is directly supported by Barnes' study.

4.2.1.i The pilot must be trained to configure the system both before the mission and during the mission. Loss of pilot skill may occur due to automation. Intermittent retraining and embedded training should be considered in aid design (Krobusek et al. 1989).

Explanation: Training requirements increase with the use of aiding systems because pilots must configure automated systems both before and during the mission. It is also possible for extensive automation to degrade pilot skill over time because reliable automation places fewer task performance demands on pilots. If pilots are not able to practice flight-related tasks, they will ultimately lose their ability to perform those tasks and overall system performance will degrade. The solution to these training issues is the implementation of intermittent and embedded training within the aid.

Empirical Support:

4.2.1.j Designers are not interested in tradeoffs between costs of communicating vs. costs of aiding; the necessary level of aid tailorability; and number and applicability of interface / aiding models available (Andes and Rouse, 1991).

Explanation: In a study conducted with aiding system designers, Andes and Rouse found that designers do not believe that the factors listed above affect system performance as much as: the method of task allocation utilized, the availability of aiding, the timeliness of pilot response, and pilot training requirements. Designers place higher value on this information as it affects system design.

Empirical Support: Additional research must be conducted to determine whether designs that do not incorporate aiding tradeoff, aid tailorability

level, and interface / aiding model information are of a poorer quality than systems that do incorporate this information.

4.2.2 Implications on Workload

Adaptation of the operator or aid can affect the workload that either of these agents experience. In cases of static adaptation, workload may be initially increased due to the reallocation of tasks during the process of adaptation. In dynamic adaptation, the process of adaptation is continuous for the agent of adaptation. Human performance characteristics, relative abilities, and context must be considered when analyzing the effects of agent of adaptation on resulting workload.

Guidelines

4.2.2.a Long lists of information, tasks, etc. should be stored and prioritized by the aid to minimize the number of decision alternatives and reduce the visual processing load of the human operator (Barnes, 1981).

Explanation: In multi-task environments, the aid should prioritize and store tasks to be performed. This will minimize workload in terms of both decision making and visual processing requirements.

Empirical Support: This guideline has been supported by Greenstein and Revesman (1986), and Sage and White (1984).

4.2.2.b Adaptive aiding and decision utility techniques are particularly applicable to situations where humans must solve complex problems that do not yield to analysis or strict adherence to doctrine or standard operating procedures (Weisbrod, Davis and Freedy, 1977).

Explanation: Adaptive aiding and decision utility assessment are well-suited for complex problem situations. The flexible nature of adaptive systems allows the aid to address tasks that it would perform best, and allows the human to address other tasks. Adaptive aids minimize operator workload because the aid can perform repetitive and boring tasks, leaving

the human to perform complex tasks that the aid might not be capable of performing.

Empirical Support: Support for this guideline is provided in this study.

4.2.2.c Consider operator fatigue in the design of an aiding system. Increased aiding may be necessary; task demands that were acceptable at the beginning of a task may impose high workload later, when the operator becomes fatigued (Morris, Rouse, Ward and Frey, 1984).

Explanation: Operator fatigue is directly related to the concept of workload. When the operator experiences fatigue, he perceives increases in workload even if task demands do not change. Thus, task demands that were originally acceptable will later impose high workload and will require increases in aiding. This guideline suggests that designers account for increases in operator fatigue and workload in the design of aiding applications.

Empirical Support: Numerous studies on vigilance support this guideline, but it has not been validated within the adaptive aiding domain.

4.2.3 Implications on Operator Acceptance

Operator acceptance of an aid may be strongly affected by whether the operator or the aid does the adapting. Operator adaptation may decrease acceptance because the operator has the added responsibility to under what conditions to adapt. Alternatively, the aid that adapts without notifying the operator may also decrease acceptance of the aid. Several characteristics about the aid must therefore be considered to ensure user acceptance.

Guidelines

4.2.3.a An aid may have to be much better at executing a system task than users in order to be accepted by the user population (Rouse, 1988).

Explanation: Users often perceive their own performance as better than it actually is. Therefore, for an aid to be acceptable, it will have to perform better than the users' perceptions of their own performance.

Empirical Support: This guideline is supported by Morris, Rouse and Ward (1985).

4.2.3.b The pilot will not accept automation unless he approves of the operational relationship between the aid and himself (Krobusek et al. 1989).

Explanation: In order for the pilot to accept an aid, he must feel as if he as a certain degree of control over the aid.

Empirical Support: An interesting empirical discussion and validation of this guideline can be found in Morris and Rouse (1986), and Morris, Rouse and Ward (1985).

4.2.3.c An adaptive aid must perform tasks as accurately as the operator. To do this, the aid must unobtrusively monitor and record actual operator performance (Andes, 1987).

Explanation: The operator will not accept an aid if it interferes with task performance. Neither will he accept an aid if it is inaccurate. Therefore, an aid must monitor the operator without disturbing him. In an effort to achieve unobtrusive monitoring, Morris and Rouse (1986) have developed several techniques, including Mean Squared Error (MSE) analysis, workload modeling, and queueing models of performance.

Empirical Support: This guideline was validated in the Morris and Rouse (1986) study. In addition, Chu and Rouse (1979) show the application of some of the above techniques.

4.2.3.d Minimize the number of system variables required through operator tailoring of the system. Operator tailoring involves personally tailoring the aid to the pilot depending on the specific mission, mission tasks required, and pilot preference (Lind, 1989).

Explanation: Operator tailoring is another way to approach the operator acceptance issue. In operator tailoring, the pilot is required to attend to a minimum number of system variables, and this minimizes pilot workload. Furthermore, the aiding system is tailored to each pilot, taking into account the type of mission, required mission tasks, and pilot preferences. It is thought that acceptance will be achieved if pilots are allowed to specify how the aiding system will function.

Empirical Support: This guideline was supported in the Lind (1989) study, where pilots gave favorable reviews to operator tailoring during evaluation.

4.2.4 Implications on Situation Assessment

If either the operator or the aid are engaged in adaptation activities, the ability of either agent to assess situations will be affected. This ability will most likely be impaired due to the decreased processing capacity of the operator and the aid during adaptation activities. With less room to process information, situational information is less likely to be processed and used in an assessment.

Guidelines

4.2.4.a These factors affect the quality of the human's decisions: human's attitude towards aid; human's perception of performance criteria; the situation; his own performance; and the computer's performance (Morris and Rouse, 1985).

Explanation: Situational awareness is attained when the human makes judgments about the state of the current situation. Since situational awareness is part of the decision making process, it is also affected by the above factors. Therefore, the attitude toward the aid, the perception of performance criteria, actual performance, and computer performance all affect the ability of the human to assess situations.

Empirical Support: Although the effects of these factors have not been validated in the context of aiding systems, it is believed that these factors

do indeed interact with each other, and consequently affect overall system performance.

4.2.4.b The operator should perform system monitoring tasks some of the time by employing adaptive automation, since the aid would not always be on. This would reduce performance decrements related to vigilance because the operator is still active in controlling the system (Morrison et al. 1990).

Explanation: System monitoring tasks are especially susceptible to performance decrements related to vigilance (Morrison, Gluckman and Deaton, 1990). Morrison et al. suggest using adaptive automation so that the pilot can maintain situational awareness by performing monitoring tasks periodically. It is believed that periodically aided monitoring may benefit overall system performance because the operator would be able to maintain situational awareness without experiencing performance decrements related to vigilance.

Empirical Support: Additional research must be done in the context of aiding to insure that adaptive automation reliably minimizes vigilance related performance decrements.

4.2.4.c Make it very clear whether the human or computer is supposed to perform a particular task at a specific time and also provide a means for changing the allocation (Rouse, 1988).

Explanation: The nature of task allocation also affects the ability for the human to assess a given situation. If too many tasks are allocated to the human or if he is unsure about whether or when to perform tasks, he will not be able to maintain an awareness of the situation. This conclusion is drawn from the work of Lehner et al. (1987), who advise to provide a means to avoid user confusion in reaction to aid-initiated adaptation. Krobusek, Boys and Palko (1989) also advise against the application of a wide-spectrum pilot aid in order to preempt confusion resulting from unclearly specified task allocation. Finally, Chu, and Rouse (1979) advise to implement a method by which the user can preempt adaptation, or "take back" a task that was previously allocated to the aiding system.

Empirical Support:

4.2: Section Summary

This section discussed the implications of whether the operator or the aid is the agent of adaptation in an aiding system. The guidelines in Section 4.2 suggest that the human is the default initiator of aiding. Further, research shows that the presence of an aid positively influences human/system performance, that the aid should initiate tasks that pilots are unlikely to perform, and that pilots should be sufficiently trained in system configuration. These guidelines also promote dynamic task allocation, and emphasize the importance of high aid reliability, operator tailoring, and the minimization of tasks which induce operator fatigue. These guidelines suggest that designers should: a) implement aiding systems that are explicit about task allocation, and b) optimize the information processing abilities of the operator.

4.3 Guidelines for "When Does Adaptation Occur?"

Adaptation may occur before system operation, or in response to changing system conditions. Pre-operation adaptation accounts for off-line or static types of information that do not change throughout system operation. Once system operation begins, however, adaptation occurs in response to on-line or dynamic information that changes with varying system conditions. The timing of adaptation may affect all facets of system operation. Timing of adaptation can depend on various "intervention thresholds." Different approaches to determining the aiding triggers have been investigated; the results and implications are examined in this section.

4.3.1 Implications on Performance

A few different methods have been used to determine when system performance will benefit from the use of adaptive aiding. Timing of intervention is of paramount importance to insure that system performance is not further degraded in the transition from unaided to aided performance. These implications are discussed in more detail below.

Guidelines

4.3.1.a Use mission-mode to determine suite of functions that should be automated during specific segments of the mission (Lind, 1989).

Explanation: Before the mission, the pilot may determine for which parts or modes of the mission particular functions will be automated. This is called mission-mode tailoring. This method of automation is useful when it is not possible to dynamically apply automation in response to changing systems demands.

Empirical Support: This guideline is validated in the Lind (1989) study.

4.3.1.b Queueing model parameters of operator workload models, specifically event arrival and service time, are useful in a coarse prediction of levels of task loading in multi-task situations. Utility is limited, however. Use when accurate methods are not available (Chu and Rouse, 1979).

Explanation: Chu and Rouse have found that event arrival and service time are useful in predicting when optimal levels of workload are exceeded. Therefore, they may be used to determine when operators should be aided in order to maintain acceptable levels of performance. Since these models have only coarse predictive abilities, they should be used when more accurate methods of workload prediction are not available.

Empirical Support: This guideline was validated in the study.

4.3.1.c Modified Petri nets can be used to model operator related processes or activities, in terms of both operator information I/O and interaction I/O. These Petri nets are used to represent "when" or control knowledge associated with allocation and viable automation (Madni, 1988).

Explanation: Modified Petri nets are a useful and flexible way to model operator processes and activities. They are capable of modeling operator information input and output, and interaction input and output.

Furthermore, modified Petri nets can represent knowledge about when to allocate tasks and when to automate tasks.

Empirical Support:

4.3.1.d An aiding system should have mechanisms to store task procedures, threshold values, and estimates of aiding success (context specific, if possible). This data can be used to evaluate current performance and use feedback to improve future aid performance (Andes, 1987).

Explanation: The availability of this information is critical to the aid during system performance evaluations and in using feedback from evaluations to improve future aiding performance.

Empirical Support:

4.3.1.e Adaptation should occur when the user knows exactly how to reach task objectives; when the user generally knows how to reach objectives, but not efficiently; when the user knows little about how to reach objectives; and when user wants peripheral information (Tyler and Treu, 1989).

Explanation: Tyler and Treu believe that decision system performance will be maximized when adaptive aiding occurs in the situations listed above. Adaptation situations have also been discussed in Guideline 4.3.1.f (Andes, 1987) with a focus on a different application domain.

Empirical Support:

4.3.1.f Adaptation should occur when: an undetected operator error is committed; the operator is too busy to take on another task; allocation is desired by the operator; the operator is functionally impaired; and / or critical (life-threatening) situations exist (Andes, 1987). For application in dynamic systems control.

Explanation: Andes explains that performance of the Pilot's Associate system (a dynamic, tactical aircraft automation program) will be maximized when adaptive aiding is applied during the situations listed above.

Empirical Support: Although these specifications are consistent with the literature thus far, they have not been validated empirically.

4.3.1.g It is desirable to aid situations where task difficulty will increase because the resource demands of responding are increasing. Human operators do not subjectively perceive this situation as more difficult, even though performance deteriorates (Derrick, 1988).

Explanation: Aid should be applied when increases in task difficulty are predicted because of concomitant increases in the resource demands of making a response.

Empirical Support: This guideline has behavioral support. Although humans do not always perceive increases in task difficulty, performance deteriorates nonetheless (Wickens and Yeh, 1983). This suggests that aid should be automatically invoked when increases in task difficulty are predicted.

4.3.2 Implications on Workload

Aiding that adapts to changing system conditions may significantly affect the operator's workload profile. Specifically, such aiding may improve the individual operator's ability to perform tasks allocated to him due to the decreased overall workload. It is critical to consider, therefore, when adaptation would best be initiated in terms of workload.

Guidelines

4.3.2.a Use automation under conditions of time pressure to help the pilot cope with an increasingly complex environment (Parasuraman et al. 1990).

Explanation: Time pressured situations increase operators' perceptions of workload. Automation of tasks that are suitable for automation can decrease operator workload while increasing mission safety.

Empirical Support: This guideline is supported by the fact that automated systems are more reliable than humans.

4.3.2.b Decision errors occur when the decision maker generates a wrong individual response. This type of error occurs at medium and high information input rates (Sen, 1984).

Explanation: Workload is considered high at medium and high information input rates. Sen has shown that error behavior occurs in high workload situations when decision makers generate wrong responses for given conditions.

Empirical Support: Miller's (1969) work provided the basis for Sen's (1984) study, both of which validate this guideline.

4.3.2.c The one main difference between Ideal vs Human decision maker is that the human knows when he is being overloaded by noticing increases in the number of input characteristics he must ignore to make a timely decision (Sen, 1984).

Explanation: The human perceives increases in workload by noticing increases in the number of input characteristics that he must ignore in order to make a timely decision. The mathematically ideal decision maker also ignores input characteristics to avoid information overload, but this set of characteristics is likely to be a smaller subset than that of the human. The optimal point of aiding then, is the point at which the human ignores a critical number of input characteristics.

Empirical Support: This guideline is validated by this study.

4.3.2.d When using workload as a dimension for intervention, task characteristics used to predict workload must be augmented with the operator's perceived

workload over tasks. Based on Wickens' Multiple Resource Theory, Derrick found that the processing stages dimension is the most important of those available (Derrick, 1988).

Explanation: Perceived workload may be higher than levels of workload estimated from task characteristics. When predicting workload then, task characteristics must be amended so that estimated workload will correspond with the operator's perceived workload. Derrick also found that the processing stages dimension of Wickens' (1984) Multiple Resource Theory is most important in predicting workload. This is critical in finding at what point during information processing aiding would be most beneficial.

Empirical Support: These findings also apply to the use of implicit communication for invoking aid-initiated intervention, and are additionally supported by Wickens and Yeh (1983).

4.3.2.e Tailored logic can be employed to alter the system aiding menus to reflect the needs of the current tactical environment. This approach reduces pilot workload by dynamically customizing the menus. It can be triggered by mission-mode, situation assessment, etc. (Barnes, 1985).

Explanation: Tailored logic is an example of partitioning tasks in the cockpit, where tasks and parts of tasks are shared between the operator and the aid. Pilot workload can be reduced by dynamically customizing menus through tailored logic: the menus offer only those options that are relevant to the current mission environment. Howard, Hammer and Geddes (1988) have developed tailored logic within the Pilot's Associate system.

Empirical Support:

4.3.3 Implications on Operator Acceptance

The timing of adaptation may have critical impact on an operator's acceptance of an aiding system. Operator acceptance may be negatively affected if the aiding

occurs unexpectedly, or at a time when the operator may not desire the aiding. Some guidelines addressing this issue are enumerated below.

Guidelines

4.3.3.a Ensure that user-initiated adaptation is possible and appropriately supported, even if aid-initiated adaptation is the norm (Rouse, 1988).

Explanation: Operator acceptance of any aiding system hinges on whether or not the operator feels in control of the system (Rouse, 1988). Since the operator is ultimately responsible for system behavior, he should be able to exert direct control in the system.

Empirical Support: This guideline is supported by studies which show that operators prefer to be in control of the system. These studies include Morris and Rouse (1986), and Morris, Rouse, and Ward (1985).

4.3.3.b The pilot must always be in control of the aircraft, must be allowed to define and change his role in the system, and be able to override any aid activity (Krobusek et al. 1989).

Explanation: The levels of autonomy (LOA) philosophy (Krobusek et al. 1989) is that the pilot is able to specify when and how the aid will be active. This paradigm is based on the assumption that operator acceptance can be achieved by allowing the pilot to control the system and change its configuration at any time. Forms of this guideline pervade the adaptive aiding literature. It is specifically supported in Rouse, Geddes and Curry (1987).

Empirical Support:

4.3.3.c Use workload measurement technology (e.g., secondary task, subjective measures, psychophysical indices, etc.) to indicate exactly what component of mental workload is overloaded, otherwise the aid may off-load tasks from the pilot when his resources are not overloaded (Parasuraman et al. 1990).

Explanation: This guideline is important to insuring that the aid is invoked at appropriate times. If an aid cannot determine exactly which components of mental workload are overloaded, tasks may be off-loaded from the pilot when it is not necessary. This may result in pilot confusion and/or significant increases in workload, and in the long-run, operator rejection of the system. Workload measurement technology allows the aid to predict the overload of specific mental components. Note that this guideline also has implications for workload.

Empirical Support: Empirical support for using workload measurement technology to foster user acceptance can be found in Wickens (1984) and Lehner, Cohen, Mullin, Thompson, and Laskey (1987).

4.3.3.d Avoid excessive task responsibility trading by allowing the user to off-load and recapture tasks to and from the aid as desired (Rouse, 1988).

Explanation: The "hot potato" phenomenon occurs when the aid initiates excessive task responsibility trading between the operator and the aid. This can be avoided by allowing the user to give up tasks to the aid and get back from the aid as desired. Although this may allow the user to feel in charge of the overall system and may facilitate operator acceptance of the aid, it may result in performance hysteresis, a problem addressed in Guideline 4.3.3.e.

Empirical Support:

4.3.3.e Performance hysteresis should be avoided. Performance hysteresis occurs with cyclic introduction and removal of aiding where operator performance approaches local maxima although the general performance trend is downward (Andes, 1990). See 4.3.3.d.

Explanation: Performance hysteresis is ultimately detrimental to overall system performance. Although operator performance may approach local maxima between instances of task off-load and recapture, operator performance generally degrades. By accounting for the hot potato

phenomenon and performance hysteresis, the designer can move toward a more symbiotic operator-aid system -- one that operators will want to use.

Empirical Support:

4.3.4 Implications on Situation Assessment

The operator's perception of when adaptation should occur is important in maintaining situation assessment of both aid functionality and overall situation assessment. Although this is an important implication, only a small number of guidelines were found.

Guidelines

4.3.4.a Familiarity with the current situation and perceived normal functioning of the aid are two main factors affecting the human operator's decision of whether to use an aid. The operator should possess sufficient information to successfully address the factors affecting the system's current status (Morris, Rouse and Ward, 1985).

Explanation: So far, there is only one guideline that is associated with situation assessment in deciding when to apply aiding. Morris, Rouse and Ward have found that the human operator's decision to use an aid is affected by situational familiarity and perceived normal functioning of the aid. Thus, the operator must have a certain degree of situation awareness in order to efficiently decide whether to invoke the aid. Situation awareness will also enable the operator to ascertain whether the aid is capable of handling tasks in unfamiliar contexts.

Empirical Support:

4.3: Section Summary

This section discussed issues pertaining to to the initiation of the aid in an aiding system. These guidelines suggest that the invocation of an aid should be based on mission mode analyses, models of operator cognitive processes, the

amount of information available for decision making, the level of operator workload, and the operator's physical state. Related research shows that an aid should be invoked during increases in both time-critical tasks and the number of system variables that must be monitored, but that excessive task-trading should be avoided. As emphasized in Sections 4.1 and 4.2, user-initiated adaptation should be possible as well. These guidelines suggest that designers should: a) implement aiding systems that give operators the impression that they are actively controlling the system, and b) emphasize pilot training in order to increase operator situation assessment abilities.

4.4 What Methods of Adaptation Apply?

According to Rouse and Rouse (1983), there are three primary ways to implement adaptation in an aiding system: allocation (designating whether the operator or the aid will perform a task), partitioning (the sharing of tasks between the operator and the aid), and transformation (changing a task to make it easier to perform). These methods are discussed with regard to their effects on the aiding system. Most of the other paradigms (e.g., function aiding [Fitts, 1951; Lind, 1989], LOA [Krobusek et al. 1989], etc.) fall into the allocation type of adaptation in the adaptive aiding concept.

4.4.1 Implications on Performance

System performance depends on the designers' abilities to correctly account for all necessary variables during system design. It is also affected by the abilities of the operators to efficiently invoke aiding when it is their decision to do so. The abilities of designers and operators are influenced by the availability of the information required to make design or operation decisions. This section presents research about the issues of system, operator, and designer performance as they relate to methods of adaptation.

Guidelines

4.4.1.a Designers are particularly interested in the availability of technology to support an aiding implementation (Andes and Rouse, 1991).

Explanation: Apparently, designers are confident in what they want to do, but require more information about the methods for implementing aiding systems. Performance of designers (in terms of the types of aiding systems that are ultimately developed) will be largely affected by the availability of technology to implement aiding systems with particular methodologies.

Empirical Support: Although this was a pilot study, some support for this guideline was provided.

4.4.1.b A complete systems engineering approach is imperative to aiding systems design due to the complexity of the human-machine interface. It requires complete user control and information requirements, function allocation, and consideration of the capabilities and constraints of the system (Parasuraman et al. 1990).

Explanation: The systems engineering approach incorporates assumptions about the capabilities and constraints of the system with information requirements analyses, function analyses, and information and control requirements analyses. It is believed this approach will provide designers with a method of accounting for all of the necessary information in the design of aiding systems.

Empirical Support: The systems engineering approach has been proposed but has not been validated by an empirical evaluation of an aiding system design methodology.

4.4.1.c Critical-event logic (see Glossary of Terms) can be used to automate systems functions when mission critical events occur. Automated function suites can be based on: emergency logic, executive logic, and automated display logic (Parasuraman et al. 1990).

Explanation: High levels of system performance may be achieved by implementing critical event logic when mission-critical events occur. Depending on the situational context, automation may be invoked without pilot approval when the system matches pre-defined events with the

current events. This approach is conceptually simple, however, since it is insensitive to actual pilot performance or workload, it may not be the best way to insure acceptable system performance.

Empirical Support: Barnes (1981) considers information requirements in the face of critical events, but validation of this guideline has yet to be achieved.

4.4.1.d The LOA (levels of autonomy) paradigm may be used to circumvent problems related to allocation in systems with multiple configurations. LOA defines a set of aiding configurations, each of which specifies a degree of automation per system subfunction (Krobusek et al. 1989).

Explanation: A system developed within the LOA approach can define a set of possible aiding configurations, differing in the degree of automation per system subfunction. The pilot sets the level of system autonomy required per task as determined by mission planning task analysis or in-flight needs. The system then executes the clearly defined tasks that it has been assigned. The LOA method of aiding applies only to task allocation problems. It is therefore not useful for error compensation or multi-mode, aid-initiated aiding situations.

Empirical Support: The LOA methodology has not been validated.

4.4.1.e LOA (Levels of Automation) configurations include: no intervention; aid automatically executes tasks; aid reminds pilot of performed tasks; aid prompts pilot about important tasks; aid performs tasks when pre-specified conditions are met (Krobusek et al. 1989).

Explanation: The five possible LOA aiding system configurations are listed above. They have been developed on the assumption that task allocation should be based on sensory, cognitive, and behavioral capabilities of the pilot population. When the aid determines that task demands exceed pilot capabilities, that task should be off-loaded to the aid. Demands on the pilot's resources, however, must be considered in the context of multitask performance.

Empirical Support: The LOA methodology has not been validated.

4.4.1.f Three primary levels of adaptation are: transformation (changing a task to make it easier); partitioning (sharing a task between aid and operator); and allocation (distributing tasks between operator and aid) (Rouse and Rouse, 1983).

Explanation: These three methods of adaptive aiding were introduced at the beginning of this review and provide a useful method of classifying types of adaptive aiding.

Empirical Support:

4.4.1.g An aiding system must be "adaptive" (i.e., not mission-mode or function automation based) to be able to compensate for operator errors. Flexible automation is necessary to meet this requirement (Andes, 1987).

Explanation: To compensate for operator error, aiding systems must be flexible, must have the capacity to monitor operator error, must possess knowledge of error compensation procedures, and must have the ability to influence the system at the necessary level of input.

Empirical Support: Although this guideline has been conceptually developed, it has not been validated in an aiding setting.

4.4.1.h Adaptive automation may benefit pilot performance by preventing performance decrements related to long term monitoring, loss of situation awareness and manual skill degradation (Morrison et al. 1990).

Explanation: An adaptive approach may decrease the effects of vigilance and thereby minimize performance decrements: the pilot remains in active control of the system instead of becoming a passive observer of the system.

Empirical Support:

4.4.1.i Use decision aiding to reduce threat categories in classification tasks, reduce response categories in translation tasks, and reduce the number of available controls in selection tasks, thereby making the tasks easier to perform (Barnes, 1985).

Explanation: Adaptive decision aiding can transform tasks and make them easier to perform. This is yet another method of maximizing performance through the use of adaptive aiding systems.

Empirical Support: This method of decision aiding has to be empirically validated.

4.4.2 Implications on Workload

The methods used to implement aiding in a system may either increase or decrease operator workload levels. The operator, for example, may experience increases in workload if he is required to obtain aiding information from a display that is cluttered with irrelevant information. It is therefore important to determine what methods of adaptation optimize operator workload associated with different methods of adaptation.

Guideline

4.4.2.a In multiple task situations, attempt to distribute tasks among different resources of the human to achieve higher overall performance and reduce workload on the human (Derrick, 1988).

Explanation: In an approach that is analogous to the partitioning method of adaptation, Derrick proposes that tasks should be distributed among different human processing resources. The rationale is that distributing tasks among processing resources will prevent the overload of a single resource, thus optimizing workload and performance.

Empirical Support: This guideline is based on Wickens' (1984) Multiple Resource Theory.

4.4.3 Implications on Operator Acceptance

The methods used to implement aiding in a system have a direct affect on operator acceptance because these methods determine how the operator and aid will interact.

Guideline

4.4.3.a The beliefs and philosophies of designers are likely to affect the types of aiding chosen. Consider whether the resulting aiding system will be either human-requirements centered or mission-requirements centered and design accordingly (Andes and Rouse, 1991).

Explanation: The designers' approach to aiding is likely to affect operator acceptance of aiding systems because the approach will be visible in the final design. Andes and Rouse suggest that designers approach design by determining whether a system will be human-requirements centered or mission-requirements centered. This approach may foster operator acceptance because design is based on the orientation of the user.

Empirical Support: This is the first formulation of such an approach to aiding design. Further research must be conducted to determine how design philosophy affects system design, as well as how beliefs might be used to specify system behavior based on user or mission requirements.

4.4.4 Implications on Situation Assessment

We were not able to extract any guidelines which addressed methods of adaptation in the context of situation assessment from the references included in the bibliography.

4.4: Section Summary

This section discussed methods that designers may use to specify aiding requirements in the design of aiding systems. These guidelines propose that

systems engineering methods, critical-event logic, levels of autonomy, levels of adaptation, and decision aiding techniques may be used by designers to determine their approach aiding system design. These guidelines suggest that designers should: a) distribute tasks among the operators' information processing resources, and b) design the aiding system to satisfy either operator requirements or mission requirements.

4.5 How Is Adaptation Done?

There are two ways to determine the needs for adaptation in a given situation. One method involves measurement of operator or system performance, and the other involves modeling operator resources, intentions, or system. These methods provide designers with the information necessary to determine how to best implement adaptation within a system.

4.5.1 Implications on Performance

The ways in which designers approach aiding the operator may affect system performance. Subsequently, the final implementation of the aid may facilitate or inhibit required levels of operator performance. It is therefore important to consider which methods of assessing aiding needs are accurate.

Guidelines

4.5.1.a Designers are interested in relationships among tasks and appropriate types of aiding appropriate within a specified task context (Andes and Rouse, 1991).

Explanation: Experimental and subject debriefing data in the Andes and Rouse investigation showed that designers need information about how the type of aiding implemented in a system may affect task performance. Designers also consider contextual influences on how the type of aiding will affect human and system performance.

Empirical Support: The study by Andes and Rouse supports this and the following two guidelines.

4.5.1.b Designers are interested in information about appropriate invocation criteria for different types of aiding (Andes and Rouse, 1991).

Explanation: The study revealed that designers find it important to consider how and when aiding should be invoked, and how different types of aiding might affect system performance. For example, if aiding is not automatic and operators find it difficult and time-consuming to invoke the aid, system performance is likely to suffer.

Empirical Support: The study supports this guideline.

4.5.1.c Designers are likely to value data that compare types of aiding and appropriate invocation criteria as a function of types of task and the motivation for aiding. Designers also prefer to make decisions based on specific and concrete information rather than general principles (Andes and Rouse, 1991).

Explanation: This guideline ties the previous two together. As stated, designers believe that system performance is likely to be affected by the type of aiding implemented and the way it is invoked. Thus, designers find it important to consider these factors in the context of the task and the conditions for invoking the aid. Designers probably prefer basing design decisions on specific and concrete information because they can be more confident that they will make correct decisions with this type of information.

Empirical Support: The study supports this guideline.

4.5.1.d The importance of aiding any task changes depends on the current demands of the situation. Therefore, the level of aiding and the ways the human and aid interact should change with changes in task demands (Rouse, 1988).

Explanation: In dynamic situations, the criticality of a given task changes with regard to the demands of the current situation. This implies that the level of aiding and human-aid interaction must also change with regard to situational demands in order to optimize system performance.

Empirical Support: This guideline is the basic premise of the concept of adaptive aiding.

4.5.1.e The operator's aiding needs depend on both impending and recently completed task demands (Rouse, 1988).

Explanation: It has been found that the demands of both anticipated and completed tasks affect the operator's needs for aiding (Morris and Rouse, 1986). If a difficult task has just been completed, for example, an operator's ability to perform a current task may be decreased. The existence of these "carryover" effects implies that aiding should be adapted to both passing and forthcoming task demands.

Empirical Support: Support is provided in Morris and Rouse (1986).

4.5.1.f The degree of task structure will dictate the accuracy with which inferences of activities, awareness, and intentions can be made when using models as a basis of adaptation (Rouse, 1988).

Explanation: Tasks with substantial levels of variability in user performance are not suitable for model-based adaptation. For example, if a model cannot account for the way a user customizes aiding, the model cannot accurately predict when during task performance adaptation should be invoked.

Empirical Support: This is a conceptual guideline; it does not yet have empirical support.

4.5.1.g Secondary indices of user and system behavior may be used as proxy measures of the primary indices of concern (Rouse, 1988).

Explanation: This guideline implies that indirect measures can be used to obtain information about user and system behavior, which may consequently indicate the need for aiding. For example, workload may not be measured directly because it is difficult to quantify with one objective measure. This guideline would suggest using temporal patterns of user and system behavior to indicate when workload is high and therefore, when aiding is necessary.

Empirical Support:

4.5.1.h Input information about operator behavior (e.g., current resource loading, manual performance, operator errors, and knowledge of intent) can be used as aid-initiated aiding thresholds (Andes, 1987).

Explanation: There are several ways to indicate to a system when aiding should be applied. Andes suggests using specific levels of resource loading, performance, error frequency and deviations from intent as thresholds for aiding systems to initiate aiding. This method is not likely to degrade system performance because, by gathering operator performance information via secondary measures, the system remains unobtrusive to operator performance.

Empirical Support:

4.5.1.i When assessing instantaneous tracking performance (generally) RMS tracking error is _not_ a good estimator.

Explanation: Guideline 4.5.1.i appears valid in most control situations, but Morris and Rouse have shown that RMS tracking error analysis is not a good estimator of tracking performance. They show that context has a strong influence on tracking performance and that RMS error analyses do not account for this influence. Instead, they suggest analysis of event arrival rates as a secondary index of possible speed-accuracy tradeoffs in performance.

Empirical Support: Support is provided in the study.

4.5.1.j Adaptive aiding interfaces should allow the user to receive direct assistance in planning how to carry out the intended task. This can be achieved by modeling system tasks and representing this hierarchy within the aiding system (Tyler and Treu, 1989).

Explanation: Modeling system tasks and representing a task hierarchy within the aiding system interface may be a good way to achieve adaptive aiding. Users have direct access to aiding information when it is displayed in the interface in a structured form. In addition, management models of system communication and collaboration can be useful in design, and have been commonly specified by different researchers.

Empirical Support: This guideline is supported in the study.

4.5.1.k A matrix of models approach can be used to estimate point performance of the operator (e.g., signal detection probability, choice selection reaction time, choice selection speed/accuracy tradeoff, reach and touch timing models, etc.). *Prediction* of performance requires a more integrated approach, however. (Andes, 1987).

Explanation: By creating matrices of models, Andes suggests that it would be possible to incorporate such predictors of performance as signal detection probability, choice selection reaction time, speed/accuracy trade-off assessment, and reach-and-touch timing models into estimations of performance. Such a matrix would be useful for aid-initiated adaptation of system performance at particular points in time. The matrix approach would not be useful if predictions of performance were required.

Empirical Support: Validation in realistic task environments has not been performed.

4.5.1.l Use pilot performance models to understand pilot behavior and trigger aiding (Parasuraman et al. 1990). These models should be wide-scoped and non-intrusive. Examples are: intent inferencing (Rouse, et al, 1987);

Multiple Resource Theory (Wickens, 1984); queueing models (Rouse and Chu, 1979); and central executive models (Barnes, 1985).

Explanation: Parasuraman et al. suggest that designers use pilot performance models to explain pilot behavior. Additionally, they suggest implementing such models in aiding systems as a way to notify the aid to initiate aiding. Performance models supply more information than behavioral measurement methods because they account for a larger number of workload parameters and may be adjusted for individual operators. Examples of performance models are listed in the guideline.

Empirical Support:

4.5.1.m Modeling of human behavior for aid-initiated intervention should at least include: task execution goal states; environment representation (graphical); situation assessment information; and planning and commitment logic (Andes and Hunt, 1989).

Explanation: Andes and Hunt propose several information requirements for modeling human behavior in aid-initiated intervention situations. The authors propose that in order to effectively intervene, an aiding system would have to possess information about the operator's goals, the problem context, the current situation, and methods for behavioral prediction. These types of information were used in a limited experimental control system to initiate aid interaction, but the model of human behavior developed was crude.

Empirical Support:

4.5.1.n Implementation of models of human performance in an aiding system can increase human performance without degrading performance of the aid (Revesman and Greenstein, 1986).

Explanation: Revesman and Greenstein have implemented models of human performance in an aiding system and have studied how the use of such models affects system performance. This guideline was the result of

an investigation that analyzed the use of model-based communication to facilitate dynamic task allocation in a multi-task environment. They found that the use of communication models supplemented human performance and did not affect performance of the aid.

Empirical Support: This guideline was validated in the Revesman and Greenstein study.

4.5.2 Implications on Workload

Optimization of workload is necessary to successful aiding system implementation. The designers' approach to adaptation has a direct bearing on operator workload levels.

Guidelines

4.5.2.a The aid should provide aid-initiated intervention so as not to increase the already high pilot workload (Krobusek, Boys, and Palko, 1989).

Explanation: The basic premise of adaptive aiding is to aid operators' performance of tasks, to do so without requiring operators to ask for assistance, and for an aid to adjust to the individual operator and the context of the situation. This goal of minimal pilot workload would not be achieved if the pilot was required to invoke aiding (Morris, Rouse and Ward, 1985; Rouse, 1988).

Empirical Support:

4.5.2.b Compatibility between stimulus (S) and response (R) can be achieved by: close geometric proximity of S and R equipment, isomorphic relationships between S/R configurations, and cognitive similarity of stimulus code and response modality (Barnes, 1981).

Explanation: Pilot workload in pilot-computer interactive situations may be minimized through design of the interface. In particular, the way the stimulus (S) is perceived and the response (R) it requires should be compatible. Barnes provides several ways to achieve S/R compatibility in

the interface. Among these methods are close proximity of S and R equipment, isomorphic relationships between S/R configurations, and cognitive similarity of S and R modalities.

Empirical Support: It is believed that these methods would facilitate pilot-computer interaction by minimizing workload, but this guideline has not been widely validated.

4.5.2.c Dynamic assessment of pilot workload provides the rationale for implementing automation in an adaptive rather than fixed manner. Direct assessment (e.g., psychophysical measures) and indirect assessment (e.g., subjective measurement) are alternatives (Parasuraman et al. 1990).

Explanation: Methods for dynamic assessment of pilot workload have been discussed in detail by Parasuraman et al. and are presented in Guideline 4.5.2.e. The authors suggest that dynamic workload assessment is necessary in adaptive aiding systems because it would allow automation to adapt to the changing needs of the pilot in a given situation. Further, dynamic aiding is likely to lead to better system performance than fixed or static aiding.

Empirical Support: Although subjective measurements of workload have undergone recent improvements, the use of these measures as the basis of aid-initiated adaptation must be further researched. Derrick (1988) and Wickens (1984) have also addressed subjective and dynamic measures of workload.

4.5.2.d Dynamic workload can be assessed as a function of: current subjective distance from a desired goal, time to reach the goal, and level of operator effort required to achieve the goal given the time available (Parasuraman et al. 1990; Hancock and Chignell, 1988).

Explanation: Parasuraman et al. have found that dynamic workload assessment is affected by the several factors listed in this guideline. The perceived distance from a desired goal, time required to reach the goal, and required level of operator effort all compound the operator's level of

workload. Increases in any of these factors correspond to increases in workload.

Empirical Support: Hancock and Chignell (1988) have provided the necessary validation of these measures in dynamically determining levels of workload in particular contexts.

4.5.2.e Dynamic psychophysiological assessment can be used as a workload measure. Methods of measurement include: pupillary dilation, heart rate, EEG, ERP, and eye scanning and fixation measurements (Parasuraman et al. 1990).

Explanation: Although these psychophysiological methods of dynamic workload assessment can be obtained continuously (a truly dynamic assessment), they are expensive, potentially intrusive, and of unknown reliability. Using them in conjunction with behavioral measures, however, may provide additional information than other workload assessment methods alone.

Empirical Support: The reliability of these methods requires further investigation. Further research is also required to determine how well psychophysiological methods correlate with static and subjective workload assessment methods.

Implications on Operator Acceptance

The methods of aiding implementation affect the operator at the interface to the system. It is necessary for the operator to be able to communicate with the system at a desirable level of interaction in order to achieve operator acceptance.

Guidelines

4.5.3.a The aid must assist the operator without interfering in those tasks that the operator is executing, and do so efficiently (Andes, 1987).

Explanation: Simulation observations suggest that operators will deactivate an aid if they perceive that it is interfering with performance of their tasks. This will occur even if the aid is assisting performance of important system tasks. Designers must be aware of this issue during the development of their aid implementation plans in order to promote operator acceptance of the aid.

Empirical Support: Although the validity of this guideline may seem obvious, it has not been tested empirically.

4.5.3.b The system must support allocation from human to machine: It must be responsive to pilot workload, pilot preference, current pilot activity, and mission contingencies for reallocation (Krobusek et al. 1989).

Explanation: Intelligent operator interface systems, including the Pilot's Associate system, have been developed on the premise that an aid should support the allocation of tasks from the human to the aid. Krobusek et al. propose that in order to fulfill this premise, an aiding system must adapt to changing levels of workload, pilot preferences, current pilot behavior, and previously defined contingencies for task reallocation. Operator acceptance may be facilitated through adherence to this guideline.

Empirical Support: Additional research is needed to determine the extent to which operator acceptance would be promoted by the designer's consideration of the above listed factors.

4.5.3.c Adaptive aiding systems should allow the user to execute an action by directly expressing high level intentions. These intentions should be recognizable by the aiding system as explicit plans of action executable within the system (Tyler and Treu, 1989) (Rouse, Geddes and Curry, 1987).

Explanation: The execution of actions by direct expression of high-level intentions was also proposed by Rouse, Geddes and Curry (1987) and Noah and Halpin (1986). If direct expression of intent is to be possible in an aiding system, the system has to be capable of recognizing intentions

as explicit plans for action. Therefore, designers must represent operator tasks as plans to the aiding system. This also requires that the system has enough domain knowledge to account for the relationship between system components and system capabilities. It seems possible that operator acceptance of an aiding system will be fostered if the system is able to correctly interpret intentions as plans of action.

Empirical Support: Expression of operator intent within a system is an ambitious goal and has yet to be successfully validated. Geddes (1989), however, has evaluated expression of implicit operator intent within an experimental control task.

4.5.3.d The aid must reflect the operator's mental model of an ideal executive assistant for optimal system performance. The aid can determine this estimate by user performance modeling or current system status measurement (Andes, 1987).

Explanation: Operator acceptance may be promoted if an operator feels as if the aiding system approximates his image of an ideal assistant. This requires that the system knows what the operator expects of system performance. If an aid cannot incorporate at least a rough estimate of the operator's mental model of an ideal assistant, then it is likely to fail the test of user acceptance. Methods for determining models of the ideal executive assistant include the use of performance modeling or current system status measurement.

Empirical Support: This guideline has been developed from anecdotal evidence in the Pilot's Associate evaluation, and therefore requires a substantial amount of additional research.

4.5.3.e Use adaptive pattern classification techniques to track a decision maker's responses in decision support systems. This information can be used to learn the decision maker's utilities and provide customized decision support based on dynamic utilities for alternatives (Weisbrod et al. 1977).

Explanation: Weisbrod et al. created models of decision making using the adaptive pattern classification method. These models were then used to estimate decision maker utilities, and to provide customized decision support. An experiment showed that subjects who received aiding based on utility estimation made significantly fewer deviations from their own maximum expected utility, and were significantly less variable in their responses than unaided subjects. Greater decision output was also observed in the aided subjects.

Empirical Support: Although positive performance measures are likely to lead to operator acceptance of an aid, additional validation should be performed to insure that this type of aiding is indeed operator accepted. Madni (1988) discusses decision maker utility estimation techniques in more detail.

4.5.4 Implications on Situation Assessment

Aiding implementation methods affect the ability of the operator to assess situations because these methods determine how the operator will interact with the system. The operator must be able to make efficient situation decisions based on the information provided by the aid, and further, the aid must not overload the operator with demands on his attention.

Guideline

4.5.4.a The aid must have a framework by which it limits its demands on pilot attention to critical interactions, allowing the pilot to maintain awareness of system activities (Krobusek et al. 1989).

Explanation: It is imperative that pilots remain aware of system activities as well as events occurring outside the system. For an adaptive aid to successfully maintain pilot awareness, the aid must limit the demands that it places on pilot attention. Such demands should be limited to predefined, critical system interactions. The LOA (Levels of Autonomy) paradigm proposed by Krobusek et al. does indeed limit demands placed on pilot attention, allowing pilots to specify before the start of a mission when they

would prefer to be notified of critical situations, and when they would prefer that the aid initiate aiding automatically. Andes (1990) and Lind (1989) address aiding implementation issues that may affect pilot ability to assess situations. They are discussed in Section 4.2.3.

Empirical Support: Further validation of using LOA to insure pilot situation awareness during aiding is required.

4.5: Section Summary

This section discussed how designers may implement the invocation of aid in aiding systems. These guidelines promote the use of operator performance criteria, the influence of both impending and recently completed tasks, operator planning/intention and models of human performance to guide design decisions about aid invocation. In addition, research suggests that aid-initiated intervention is critical in aiding systems. These guidelines suggest that designers should: a) minimize the demands of aiding systems on operator attention, and b) implement systems that are both perceptive and responsive to operator intention.

4.6 What is the Nature of Aid-Operator Communication?

The operator and the aid communicate information either before or in response to the effects of adaptation. This communication may be either explicit, comprising part of the operator-aid interaction task, or it may be implicit, occurring "behind the scenes" during task performance. Communication between the aid and the operator is a paramount issue. Efficient communication can significantly increase performance on several dimensions (i.e., situation assessment, coordination of activities). Inefficient communication can result in degraded system performance (e.g., repeated activities, confusion about task responsibility) and ultimately, system breakdown.

4.6.1 Implications on Performance

The communication between aid and operator may affect system performance. If the aid or the operator do not receive accurate or complete

information during communication, decrements in performance will occur. It is necessary therefore to insure that optimal methods of communication are implemented within adaptive aiding systems.

Guidelines

4.6.1.a The cost of explicit communication (e.g., workload and time required) with the user should be compared with the cost of adaptation errors (i.e., misses and false alarms). This guideline is applicable primarily to user error events (Rouse, 1988).

Explanation: The process of communication between the aid and the operator will affect system performance. Revesman and Greenstein (1986) addressed the costs of the different types of communication with regard to user error events. Rouse has further addressed how communication may affect user and system performance. Apparently, although explicit communication may improve user and system performance in terms of reduced misses and false alarms, it is expensive in terms of added workload and time required for communication. Implicit communication, though less expensive, may not improve performance to the same extent as explicit communication. Rouse suggests that designers should compare the cost of explicit communication with the user to the cost of aiding errors; the system should use the cheapest communication possible resulting in a tolerable level of aiding performance.

Empirical Support:

4.6.1.b The aid must justify advice to human based on fallible algorithms. Whether a human decides to use advice depends on how he chooses to use the aid, and the discretion he uses in accepting or rejecting the advice (Lehner et al. 1989).

Explanation: Aiding systems base their advice on algorithms that are not perfectly accurate. Operators may not be aware of this fact, but may nevertheless be in a position where they must decide whether or not to accept the aid's advice. In an empirical setting, Lehner et al. found that

task performance is best when the aid's advice is routinely accepted or rejected, when operators regularly follow or ignore aiding advice. These results imply that operators who put only some trust in the aid's advice will not perform as well as operators who put all of their trust or none of their trust in the aid. For optimal performance, operators should be aware of this phenomenon.

Empirical Support: The Lehner et al. study supports this guideline by showing that performance is affected by operators' discretion in using an aid's advice. Morris and Rouse (1986) discuss user discretion in the context of information requirements for communication.

4.6.1.c Variable display formats are useful in situations where operators have habituated to certain types of signals and response latencies are increasing (Forester, 1987).

Explanation: This guideline implies that communication between operator and aid may be facilitated by changes in display format once the operator begins to habituate to one type of format. Forester developed this concept with regard to Wickens' (1984) Multiple Resource Theory. Although it may facilitate communication, changing the way an operator interacts with an interface by changing the way information is presented may or may not have detrimental effects on system or human performance.

Empirical Support:

4.6.1.d The dialogue between the adaptive system and the user must be appropriate to the user and the application for which the system is designed. Consider target user vocabulary and capabilities of each user population to facilitate maximum information bandwidth (Norcio and Stanley, 1989).

Explanation: Norcio and Stanley have addressed the methods by which communication may occur in an adaptive system. Through experiments they have found that the dialogue between the system and the user must be appropriate to the user and to the tasks for which the system was

designed. To insure optimal information throughput during aid-user communication, designers should consider the target user vocabulary and the capabilities of different user populations, and should design the aiding system accordingly. This guideline is especially useful for systems used by several user populations.

Empirical Support: The Norcio and Stanley study provides support for this guideline. In addition, Morris and Rouse (1986) have addressed methods of communication and their effects on performance with regard to dynamic task allocation.

4.6.1.e Model-based communication (implicit) between operator and aid is desired when operator workload is high, or when minimization of a particular measure of system cost (i.e., response time) is necessary (Revesman and Greenstein, 1986).

Explanation: It is possible to use models of operator-aid communication to initiate aiding when operators are under high workload conditions. This will benefit system performance because model-based communication is implicit to the system and does not require operator attention. Further, implicit communication methods impose minimal system performance costs, and may provide the basis for aiding intervention thresholds, intent inferencing, and tailored resource modeling. Though little empirical support for this guideline exists, the implicit communication that is afforded by modeling has been espoused by Rouse (1988) and Rouse, Geddes and Curry (1987).

Empirical Support:

4.6.1.f Use model-based communication between the operator and aid when the aid cannot communicate its actions to the operator. This enables the aid to work around the operator and reduce the number of redundant actions (Revesman and Greenstein, 1986).

Explanation: Revesman and Greenstein suggest using model-based communication when explicit communication between operator and aid is

not possible. Model-based communication allows the aid to determine possible operator actions. If the model predicts that the operator will perform certain tasks, the aid will perform other necessary tasks. Not only will this method maximize system efficiency, it will reduce the number of redundant actions that the aid might perform.

Empirical Support: Validation of this guideline is necessary to find whether operator ignorance of the aid's functioning will negatively affect system performance.

4.6.1.g Where possible, an analysis should be conducted to determine the extent of loss of system performance due to imperfect model validity (for communication) traded against the loss of system performance due to time required for explicit dialogue (Revesman and Greenstein, 1986).

Explanation: Revesman and Greenstein suggest analyzing the effectiveness of model-based communication when time constraints permit. This will allow the system to determine how performance is affected by improper fit of the model to the task context. The system should then determine how performance is affected by the time-related cost of explicit operator-aid dialogue. The system should note whether the cost to performance of imperfect model fit or explicit communication is lower, and should implement that alternative.

Empirical Support:

4.6.1.h A two stage model can be used to predict decision making and action in human-computer interaction: 1. Human event detection is modeled by generating the probability of response to an event; 2. Control actions are predicted using the estimated probabilities. Use as an alternative to explicit communication (Greenstein and Revesman, 1986).

Explanation: As discussed, explicit communication between the operator and the aid is time-expensive. Greenstein and Revesman have proposed a model by which explicit operator-aid communication can be avoided. In this two-stage model, the system first models the probability that a human

will detect and respond to an event. Second, the system predicts operator control actions using the estimated detection and response probabilities. This method allows the selection of optimal aiding actions based on predictions of humans' actions, and is considered a practical alternative to explicit communication. A queueing model of human decision making has been described by Chu and Rouse (1979).

Empirical Support:

4.6.1.i When info must be updated quickly, the most important information should be cued to insure that these items are the first to be processed off of the sensory register (Barnes, 1981, from Sperling, 1961).

Explanation: This guideline is often overlooked during the design of information displays in aiding systems. Barnes states that cueing important items helps insure that they will be the first to be processed by the operator.

Empirical Support: This guideline is a basic information presentation guideline and was developed from the work of Sperling (1961). Sperling showed that cued information is the first information processed off of the visual sensory registers.

4.6.1.j Stress spatial representation of information and symbols during overload situations involving tracking tasks. Increased performance on the task often results (Barnes, 1981).

Explanation: In tracking task scenarios, mental overload may be reduced if information is presented spatially or graphically. Better task performance is likely to follow reduced levels of overload.

Empirical Support: This guideline is based on a study by Baddeley and Lieberman (1980) that showed increased performance of tracking tasks when information was transformed to a spatial representation format.

4.6.2 Implications on Workload

Communication between operator and aid can result in increased workload for either or both agents. If it is explicit, it imposes another task on the operator. If communication is implicit, however, the operator's workload may not be affected because the operator does not have to make an effort to communicate his actions to the aid. Implicit communication is, understandably, more difficult than explicit communication.

Guidelines

4.6.2.a A good decision aid should reduce the number of response options in the cockpit. This research showed that response loading factors, and not number of threats were the bottleneck for a threat evaluation task (Barnes, 1985).

Explanation: Workload will be reduced if the number of possible response options in the cockpit is minimized. Barnes' study showed that the number of responses, not the number of threats perceived, was the main source of increased workload in a threat evaluation task. This implies that pilot - decision aid communication should be designed so that required pilot responses are minimized.

Empirical Support: Validation is provided by Barnes' study.

4.6.2.b Information presentation rate should not exceed the short term memory (STM) span of about 7 items in active memory at once (Barnes, 1981, from Miller, 1956).

Explanation: If a system communicates more than 7 items of information to the pilot at once, the pilot will experience overload. Designers should therefore configure decision aids to assist decision making when operators have to account for 7 or more items.

Empirical Support: Miller's work (1956) and numerous replications of his work support this guideline.

4.6.2.c Utilize spatial representations of aiding information (where possible) instead of verbal or textual displays in high workload situations (Barnes, 1981).

Explanation: In high workload situations, humans are better able to attend to spatial representations. Barnes suggests, therefore, that they be used wherever possible, particularly in high workload situations. One caveat to this guideline is not always easy or even possible to create spatial representations of information .

Empirical Support: Baddeley and Lieberman (1980) provide support for this guideline, showing that spatial working memory is used to store information about the relationships about objects in space. In addition, Baddeley and Lieberman have found that if information is presented spatially, the probability of developing a high workload situation is reduced.

4.6.2.d Model-based communication systems should be used in real-time systems where the aid's actions may parallel operator actions. This approach allows the aid to reduce workload while maintaining the operator's perception of control (Revesman and Greenstein, 1986).

Explanation: In order to maintain the operator's perception of control while reducing workload, Revesman and Greenstein suggest using model-based communication in aiding systems. It is believed that modeling communication processes will provide a valid substitute for actual communication. This will allow the aiding system to act in coordination with the operator without interrupting him, increasing workload, or causing error. Examples of implicit communication models have been discussed in Guidelines 4.6.1.e, 4.6.1.f, and 4.6.1.h.

Empirical Support: Additional validation is required to determine whether these models should be used in real-time systems.

4.6.2.e Dialogue-based communication should be minimized between the operator and aid. Although it allows explicit communication, it is not optimal because it may increase operator workload rather than decrease workload through aiding (Revesman and Greenstein, 1986).

Explanation: Explicit or dialogue-based communication is acceptable only in low workload situations because it places attentional demands on operators and may increase workload. In situations with increasing levels of workload, implicit (modeled) communication should be used.

Empirical Support: More validation is needed to determine at what level of workload dialogue-based communication is unacceptable.

4.6.3 Implications on Operator Acceptance

The ease with which operator-aid communication occurs will significantly affect operator acceptance of the aid. Availability of information, information bandwidth, an understanding of how the aid works, and communication about adaptation are the types of critical information that determine whether the operator accepts the aid's assistance.

Guidelines

4.6.3.a Procedural information, or information about rules or algorithms that the aid is using, allows the operator to make effective decisions in situations where those rules apply (Morris, Rouse and Ward, 1985).

Explanation: There are three types of operator-aid communication information that may affect user acceptance of an aid: procedural, process, and product information. The first two are discussed in this and the following guideline. The third is discussed in Section 4.6.4, Guideline 4.6.4.h. Procedural information is information about rules or algorithms used by the aid. Availability of this information allows the operator to make effective decisions in situations where the aid is using such procedures. Knowledge of procedural information fosters user acceptance of the aid because the operator is able to understand how the aid is functioning.

Empirical Support: Morris, Rouse and Ward showed that awareness of procedural information increased operator acceptance of the aid.

4.6.3.b Process information or information about how the aid accomplishes tasks is necessary when the operator is considering the use of an aid in unfamiliar contexts (Morris, Rouse and Ward, 1985).

Explanation: The second type of operator-aid communication information presented by Morris et al. is process information. This information includes how the aid performs particular tasks. It was found that operators require process information when deciding whether or not to use an aid in unfamiliar situations, or when trying to identify the nature and extent of aiding malfunctions. Operator acceptance of an aid hinges on the availability of process information in new contexts.

Empirical Support: This guideline was validated in the Morris et al. study. In addition, Andes and Rouse (1991) found that procedural and process information are important to designers of adaptive aiding systems. See Guidelines 4.1.1.c, 4.1.3.a, 4.5.1.a, and 4.5.1.b.

4.6.3.c Adaptation is facilitated if the user and the aid have a good conceptual model of how each of the other agents work. Improvements in the user's model of the system are thought to be more beneficial than the converse (Lehner et al. 1987).

Explanation: This implies that gains in operator understanding of how a system functions will lead to increased probability of acceptance. Lehner et al. also believe that improvements in the operator's model of the system are more beneficial to system performance and operator acceptance than are improvements to the aid's model of the operator.

Empirical Support: Although this guideline is present in several aiding paradigms (Andes, 1987; Rouse, Geddes and Curry, 1987), it has not yet been empirically tested.

4.6.3.d Dynamic allocation (i.e., adaptive aiding) has the disadvantage of creating the possibility of conflict between aid and operator when both attempt the same task. Minimize this possibility by ensuring that each entity is aware of the other's actions (Revesman and Greenstein, 1986).

Explanation: In dynamic allocation situations, the allocation of tasks to either the operator or the aid changes over time. It is possible and perhaps likely that in such situations, the operator and the aid may attempt to perform the same task at the same time. It is therefore necessary to implement explicit communication methods in aiding systems with dynamic allocation. This will enable each agent to become aware of the other's actions, and is likely to lead to increased operator acceptance of the system. The type and amount of communication in these situations, however, must be optimized so as not to increase workload associated with communication.

Empirical Support: This guideline has been espoused by several researchers including Rouse (1988), Lehner et al. (1987), and Andes (1987). Further research is necessary to determine exactly how to optimize type and amount of communications in dynamic allocation settings.

4.6.4 Implications on Situation Assessment

The ability of the operator to assess a given situation depends on his ability to acquire information about system status from the aid. Conversely, the ability of the aid to assess a situation depends on its awareness of the operator's actions and the effects of those actions. Thus, operator-aid communication also affects situation assessment capability of any system.

Guidelines

4.6.4.a A variety of human factors principles (e.g., vigilance support, navigational support, maintenance of user context, etc.) for the design of complex systems displays apply directly to the design of adaptive aiding system displays. See Noah and Halpin (1986) for list (Rouse, 1988).

Explanation: Lessons learned from researchers in the display design community can be applied to the design of adaptive aiding systems. In particular, adherence to such guidelines in aiding systems information displays may facilitate operator-aid communication. This may ultimately increase the ability of the operator to make situation assessment decisions.

Empirical Support: Noah and Halpin (1986) have addressed display design with regard to communicating complex information. Furthermore, Barnes (1981) has summarized information display guidelines that are useful in the display of aiding information.

4.6.4.b Factors that affect display of aiding information include mode of information presentation, type of information presented, timeliness of delivery, and depth of aiding (amount of information) (Andes, 1990).

Explanation: Several factors may affect the pilot's ability to assess information in an aiding display. The designer should consider these factors during the design of the pilot-aid task allocation interface because the nature of this interface will affect the ability of the pilot to assess the state of the information presented to him.

Empirical Support:

4.6.4.c System information should be reorganized and displayed in either aggregated or disaggregated patterns depending on the state of the system. Use aggregated information displays for overall system situation awareness; use disaggregated displays to highlight errors or detailed information (Forester, 1986).

Explanation: This guideline addresses the presentation of system-relevant information to facilitate operator situation assessment ability. Forester suggests that designers consider possible states of the system and display information in either an aggregated or disaggregated pattern accordingly. Aggregated information displays should be used to display system situation information because such displays allow the operator to assess

the overall state of the system. Disaggregated displays draw operator attention to system errors and other detailed information.

Empirical Support: Forester validated this guideline in three experiments, showing that both aided and unaided performance increased when display modality was in accord with the state of the system.

4.6.4.d Avoid the application of a wide-spectrum (i.e., multi-capability) pilot aid because either the pilot or the aid can become confused as to their proper duties at a particular time (Krobusek et al. 1989).

Explanation: A wide-spectrum pilot aid may result in unclearly specified task allocation. This would limit the ability of the pilot to perform well because he would not be certain upon which tasks to focus his attention. Furthermore, since a wide-spectrum aid would cause the pilot to focus attention on task allocation, he would not be able to sufficiently assess the state of the system or the environment.

Empirical Support: This guideline is consistent with the findings of Lehner, Cohen, Mullin, Thompson, and Laskey (1987), Lind (1989), and Moss, Reising and Hudson (1984).

4.6.4.e Interaction with the aid must be time and effort efficient. The pilot must be able to readily determine system status and allocation of task between pilot and aid at a glance (Krobusek et al. 1989).

Explanation: Time and effort efficient situation assessment can be achieved if the pilot is capable of readily determining system status and allocation of tasks between himself and the aid.

Empirical Support: This guideline has been addressed in the Pilot's Associate literature, but still requires empirical validation.

4.6.4.f The aid must keep track of tasks currently being executed, task contexts that are no longer valid, and provide a mechanism for keeping the operator

abreast of its activities, for example, cross-hatch overlays of menus and termination conditions in scripts (Andes, 1987).

Explanation: An aid that is able to successfully supply situation assessment information to the operator must perform several functions. Andes states that such an aid must keep track of current tasks and invalid task contexts, and must be able to communicate its activities to the operator. Cross-hatching menus are a way to notify the operator that particular menus are no longer applicable to a situation; termination conditions in system programs are a way for the system to halt current tasks and to notify the operator of such activities.

Empirical Support: Although several approaches to communicating this type of situation awareness have been proposed, the lack of operational systems has made the validation of this guideline relatively infeasible.

4.6.4.g During design, attempt to anticipate situations in which the operator may have to intervene in automated tasks. Use this information in the design of early warning notification displays for aid failure and/or performance decrements (Morrison et al. 1990).

Explanation: Morrison et al. suggest that designers should determine in which situations aid failure would require operator intervention and should estimate the time required for operators to adjust to ensuing task load changes. Although such time estimations may be variable, designers should use these estimations to indicate how to implement early warning notification displays. Designers' estimations of pilot situation assessment ability are critical to pilot and mission survival during system failure.

Empirical Support: The ability of designers to adhere to this guideline has not yet been observed.

4.6.4.h Product information -- information about normal aiding system output -- is necessary to allow the operator to determine whether the system is functioning properly (Morris, Rouse and Ward, 1985).

Explanation: Product information is the third type of operator-aid communication information. (See Guidelines 4.6.3.a and 4.6.3.b for explanations of procedural and process information, respectively.) Product information addresses normal aiding system output and is required for the operator to validate proper system functioning. This is expected as a basic function expected of aiding systems. Furthermore, providing product information to the operator would not be difficult because such information is readily available to the aid.

Empirical Support: Morris, Rouse and Ward showed that awareness of product information increased operator ability to assess the state of the system and the external situation.

4.6.4.i Timeliness of information presentation -- If information is static (acquired before the decision point), it can be readily applied. If information source is dynamic (i.e., system feedback), it must be presented on-line to ensure a timely decision (Morris, Rouse and Ward, 1985).

Explanation: Static information is acquired before critical decision points and can be readily applied when necessary. Dynamic information (such as system feedback) differs in that it changes over time, and this requires that it is presented on-line and on-demand. Such on-line presentation is necessary to allow the operator to make timely decisions with the most current system information. Using static information may lead to incorrect decisions because it does not account for the most current state of the system. Successful incorporation of static and dynamic information within operator-aid communication will facilitate the ability of the operator to maintain acceptable levels of situation assessment.

Empirical Support: An information requirements analysis must be conducted during design to determine how much information should be presented to the operator in a given situation (Andes and Rouse, 1991).

4.6.4.j As the level of familiarity changes, procedural information becomes less applicable, and more product and process information is needed. The

value of on-line information over off-line information also increases relative to the type of information required (Morris and Rouse, 1985).

Explanation: Morris and Rouse (1986) have formed a general principle of information requirements in aiding from research addressing such requirements: "As the nature of the situation changes from familiar to unfamiliar, and/or the performance of the aid degrades, there is a corresponding change in the information requirements of the operator. The direction of the change is toward more static information with decreased situation familiarity, and toward more dynamic information with increased situation familiarity." Thus, as an operator becomes more familiar with a given situation, he requires less procedural information and more product and process information. This relates to a decreased value of off-line information and an increased value of on-line information, and implies that the operator's ability to use dynamic information improves with increases in situation familiarity.

Empirical Support: This guideline and the general hypothesis about information requirements need further validation.

4.6.4.k Immediate feedback is necessary from command and control orders to ensure successful situation assessment of aiding (Morris and Zee, 1988).

Explanation: Information that is critical to accurate situation assessment is feedback from command and control (C2) orders. In C2 situations, the decision maker must have the ability to monitor the activities of others and determine whether his orders have been properly executed. It is also important for the decision maker to easily determine whether the aid has responded to his commands. Such information is required by the decision maker to make further C2 actions and to properly assess what the system as a whole is doing.

Empirical Support: Experimentation is necessary to validate this guideline.

4.6: Section Summary

This section discussed the design of aiding systems with regard to the nature of communication between the aiding system and the operator. These guidelines suggest that designers consider the costs of explicit versus implicit communication and the appropriateness of the type of communication to the situation. Further, designers should consider the effects of whether an operator chooses to heed or ignore the aid's advice. Designers should also allow model-based communciation, and minimize displayed response options. These guidelines suggest that designers should: a) design aiding systems with the capacity to display variable information presentation formats, to cue information, and to allow the spatial representation of information, and b) design aiding system displays to promote operator/aid time and effort efficiency.

5.0 Summary and discussion

A large number of sources were reviewed in the preparation of this document. Research from systems engineering, artificial intelligence, human factors psychology, and human performance in complex systems was reviewed in an effort to cover all facets of the design of adaptive aiding systems. This review includes literature beginning with Rouse's (1975) paper and continuing through adaptive aiding research results to the present.

A total of 142 guidelines for adaptive aiding system design were compiled from over 40 references. Although each source contributed significantly to the number and quality of the guidelines, some sources had a large influence on the way the guidelines evolved. Sen (1984), for example, used decision theory to provide insight into the nature of operator / aid interaction. Likewise, Weisbrod, Davis and Freedy (1977) and Revesman and Greenstein (1986) incorporated decision theory into specifications for decision support systems. Krobusek, Boys and Palko (1989) provided significant input on the performance of aiding systems and on training requirements for such systems. Furthermore, Morris, Rouse and Ward (1985) and Morris and Rouse (1986) provided an account of user attitudes toward an aid, as well as user interaction tendencies. Finally, from a practical point of view, Norcio and Stanley (1989) discussed how adaptive interfaces may benefit users of

adaptive aiding systems, and Andes and Rouse (1991) showed what information designers value during the development of aiding systems.

The guideline taxonomy constructed from Rouse's framework for design appears to address all issues concerning adaptive aid design. It serves three major purposes in the current review context: First, it provides quick reference structuring for immediate access to specific design information and cross references the information on projected implications of the information on aid design. Second, it highlights where most of the research to date has been focused and shows where research is needed to fill out the concept. Finally, it provides a robust structure for future formulation of design guidelines. Table 2 provides a statistical summary of the guidelines in this document.. There are two numbers in each cell of the table: the first represents the number of guidelines that apply to that area of the taxonomy, and the second represents the number of guidelines with empirical support.

DESIGN FRAMEWORK QUESTION	PERFORMANCE	WORKLOAD	USER ACCEPTANCE	SITUATION ASSESSMENT
What is adapted to?	17 / 8	10 / 5	8 / 3	3 / 2
Who does the adapting?	10 / 7	3 / 2	4 / 4	3 / 0
When does the adaptation occur?	7 / 4	5 / 4	5 / 2	1 / 0
What methods of adaptation apply?	9 / 1	1 / 1	1 / 0	0
How is adaptation done?	14 / 7	5 / 1	5 / 0	1 / 0
What is the nature of operator-aid communication?	1 0/ 4	5 / 3	4 / 3	11 / 5
TOTALS	67 / 31	29 / 16	27 / 12	19 / 7

Table 2 - Design Guideline Classification Taxonomy

Generally, the taxonomy served as a useful organizational tool for design guidelines. We may desire to augment the framework in the future, specifically in the implications area. Possibly, implications on implementation difficulty should be added when more systems are deployed and lessons learned are compiled. Basically, we will be producing guidelines about better ways to implement aid functionality.

Although quite a few useful design guidelines were extracted from the literature, one can see that most of the guidelines are concerned with what agent or task is adapted to, and how that adaptation should be accomplished. Specifically, a large number of guidelines addressed various issues in terms of resulting system performance. This is a logical observation, because the motivation behind adaptive aiding technology is to increase overall system performance by augmenting the operator's performance through task assistance and workload reduction. However, the other two affect areas (user acceptance and situation assessment) are in dire need of research support.

Applicability of types of aiding is another area in need of research support. The "meta-design" aiding study conducted by Andes and Rouse (1991) showed that designers are very interested in the interaction between types of aiding and applicability of these aiding types. Since there are not many implemented systems or studies analyzing different modes of aiding in the same task environment, it is expected that few guidelines would be extracted. This is a prime area for future research, however. Without such information, the relative applicability of different types of aiding will still be in question. Further, as adaptive aid design becomes more of an engineering process, rather than art, there is a need for aid functional consistency. The interaction characteristics between operator and aid should become more consistent within specific (i.e., aircraft cockpits) domains.

More investigation into the design philosophy underlying the resulting aiding system also needs to be conducted. As can be seen in the number of guidelines pertaining to the automation approach taken and functions to be allocated, the philosophy of aiding is the most important consideration in design. There is a need, however, to develop specific guidelines about when an automation approach is more applicable than another.

Finally, less emphasis needs to be placed on models of human performance and resulting guidelines. Rather, more emphasis should be placed on how the operator views the partnership between operator and aid. In particular, development of models that consider operator task loading, internal psychological factors, and *then* system performance implications on aiding ought to be developed.

6.0 Future directions

This document is the second step in the production of a comprehensive reference of adaptive aiding design guidelines. The aiding systems designer, as stated early on in this document, must be familiar with several diverse fields of research: human factors psychology, software engineering, human performance, etc. It is unreasonable to assume that the systems designer would be intimately familiar with all related fields. Instead, it is the adaptive aiding researcher's responsibility to educate potential designers about sources of information and directions on how to use that information during the design process.

Towards that end, it appears that the taxonomy developed during this review will serve as a reasonable framework for the expanding guidelines reference. In support of this, there are a few recommendations for future work in compiling the adaptive aiding design guidelines. First, it is essential to identify which areas are lacking significant design direction. As stated in the summary of this document, the areas most in need of useful guidelines are those concerning user acceptance of aiding and situation assessment in the presence of an aid. Future work should emphasize these areas. One could conclude that the operator-aid interaction is the area in need of guideline fortification. In addition, more concrete guidelines should be produced; researchers typically do not report results in a format intended for designers. With the implementation of more aiding systems, we should see emphasis being placed on the design process and therefore guidelines with well defined application areas should result.

Second, the breadth of sources should be expanded in the next iteration. In particular, implemented systems literature should be included to extract design guidelines from lessons learned during implementation and evaluation of the systems. Other reference sources (i.e., different databases, etc.) should be reviewed to identify useful information that was not uncovered in this pass. Accident and safety analysis information will be invaluable in fleshing out the guideline framework.

Finally, related pure and applied research from other research areas should be reviewed and included in the next iteration of the design guidelines. Although this theme was addressed in the current review, research results that were peripheral to the adaptive aiding concept (i.e., results that have bearing on, but are not directly produced from an aiding environment) were not stressed. There is a wealth of research results that could be interpreted for application to adaptive aiding design problems (e.g., vigilance studies, group decision making studies,

collaborative work analyses, etc.). The major work involved on this theme will concern proper interpretation of the results and data for aid design application.

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Glossary of Terms

adaptive aiding - A systems automation philosophy that proposes the use of automation to assist the operator only when system performance is likely to degrade past the point of acceptability in the near future (Rouse and Rouse, 1983).

adaptive automation - Another term for adaptive aiding. Stresses adaptability of automation in terms of the regulation of operator workload and vigilance, maintenance of skill levels, and task involvement at both cognitive and manual performance levels.

adaptive function allocation - Alternate term for adaptive aiding and adaptive automation. Roots founded in functional task allocation perspective of Fitts (1951).

adaptive pattern classification techniques - Founded primarily in the statistical domain, adaptive pattern classification techniques range from n-dimensional mappings of data to groups to complex pattern recognizers (e.g., neural networks). These techniques are applicable when the state space contains multi-dimensional input, output, and state vectors, and especially when normal (i.e., linear models) statistical analysis techniques do not apply.

aid-initiated intervention - A type of index of aiding system adaptation. In this case, aiding is activated by exceeding a pre-defined measurement (i.e., performance) or modeling (i.e., operator workload) threshold (Rouse, 1988).

cognitive style - The characteristic manner in which an individual perceives, thinks about, and reacts to the environment. This term is commonly seen in the context of individual differences (Hunt, 1982).

concept development - The process by which individuals acquire and parameterize new category terms for understanding of the perceived world (Neisser, 1987).

conscious overload avoidance strategy - The automatic "task shedding" behavior exhibited by human operators in high workload multi-task environments. This behavior is often observed during the period before operator task overload when the operator anticipates imminent resource overload (Sen, 1984).

context customization - A characteristic of adaptive user interfaces. Context customization features allow the user to personalize the aiding system's display presentation, create new links between system parameters, and vary the depth of information presented to the user based on user expertise (Noah and Halpin, 1989).

critical event logic - A method of automation implementation by which activation of the automation is tied to the occurrence of specific tactical events (Barnes, 1985).

decision maker's dominance structure - In decision theory, this structure is represented by the fact that a decision alternative category, x, is preferred ("dominates") over another decision alternative category, y. That is: $x_i >= y_i$; for all decision instances, i. This approach is taken to account for all decision alternative classes within context. In a dominance structure, the idea of dominance exploits only the ordinal character of the decision alternatives (i.e., simple preference of x over y), not the cardinal character of the alternatives (i.e., that x is 3 greater than y) (Keeney and Raiffa, 1976).

decision analysis - The process of determining either (or both) probabilistic or utilitarian judgments that are produced in response to special circumstances yielding alternative choices to a decision maker (Hammond, McClelland, and Mumpower, 1980).

depth of information - Detail of aiding status information supplied to the operator about the aid (see process, product, and procedural information definitions for comments) (Andes, 1990).

direct assessment - Refers to the employment of psychophysical measurements to estimate operator task and workload in determining the need for aiding (Parasuraman et al. 1990).

direct judgment - From Behavioral Decision Theory (BDT) (Edwards, 1962). A procedure used to estimate the parameters of models of decision makers' decision process. BDT frequently requires the decision maker to specify directly the relative importance of various attributes of the decision problem (e.g., by assigning numbers to them in proportion to their relative importance).

dynamic utility estimation - Statistical methods in decision analysis designed to produce probabilistic estimates of an individual's estimate for each alternative decision within a set of decision alternatives (Keeney and Raiffa, 1976).

dynamic task allocation - An approach to adaptive aiding invocation by which active and pending tasks are assigned to the operator or the aid according to changing system state, operator state, or a combination of both (Rouse, 1975).

dynamic assessment - Refers to dynamic psychophysiological estimation of operator workload based on factors such as EEG, pupillary dilation, ERP, etc. (Parasuraman, et. al., 1990).

dynamic workload - Determination of changing operator workload levels via workload estimation techniques (e.g., SWAT) .

embedded training - A type of automated training system that is a component of the aiding system itself. Embedded training allows the system to present the operator with training problems or exercises with preset scenarios using the actual aid displays and controls. Can be activated during lulls in system control requirements or off-line.

error recognition - Various artificial intelligence and pattern recognition techniques for identifying error states or possible upcoming errors based on system state and operator actions. Error recognition has been addressed in the Pilot's Associate system (Rouse, Geddes, and Curry, 1987).

environment representation (graphical) - In the context of adaptive aiding design guidelines, a pictographic or graphical representation of environment information (e.g., situation assessment) often enhances the operator's ability to assimilate large amounts of information at a glance (Morris, Rouse, and Zee, 1987).

explicit communication - Direct, purposeful communication between the aid and the operator concerning activities, awareness, and intentions of each party. Is minimally ambiguous but can impose substantial overhead and can potentially exceed the benefits of aiding (Rouse, 1988).

framework for adaptive aid design - A set of conceptual design issues addressing the systematic conceptual design of adaptive aiding proposed by Rouse, 1988. The designer pursues answers to the set of structured design questions aimed at forming a conceptual framework for the aid to be designed. While it is not possible to provide generic, context-free answers to the questions, it is possible to outline the range of alternative answers and suggest principles of adaptation and interaction that may assist designers in choosing among the alternatives. This framework also provides the fundamental structure for the current listing of design guidelines. See Section 3.0 for further explanation.

function aiding - After Fitts (1951). This general automation design approach seeks to first identify those tasks that are best suited to automation, then introduce automation to address the task based on the functions necessary to complete that task. Also espoused in the work of Lind (1989) and Krobusek et al. (1989).

hot potato - A possible effect of aid-initiated task re-allocation in adaptive aiding. In this phenomenon, the system has adapted to the point where performance is acceptable on all tasks with which the human is involved. Since performance is now acceptable, the aid could possibly return execution responsibility of a partially completed task back to the operator, resulting in an increase in operator workload. This potential dilemma is inconsistent with the operator-in-charge philosophy, as increased workload, degraded performance, and confusion could result (Rouse, Geddes, and Curry, 1987).

human-performance-centered - An approach to systems automation emphasizing support of operator manual tasks (e.g., tracking).

human-requirements-centered - An archetypal approach to systems automation emphasizing support of the human system operator over satisfaction of task requirements. Contrast with task-requirements-centered (Andes and Rouse, 1991).

incomplete decision responses - A result of "conscious overload avoidance strategy." See above. In this context, decision makers provide partial decisions in the decision space because they have only considered certain segments of information necessary to provide a complete decision response. After Sen (1984).

indirect assessment - A type of performance or workload determination used when direct assessment is not available. For example, in Morris and Rouse (1986), a secondary measure of performance, tracking response latency, was an indirect assessment of visual overload.

inference from simple gamble - Used for dynamically assessing the decision maker's utility functions. Pairwise preferences for decision alternatives are presented to the decision maker, and the preference values are stored in a database for later reference by the aiding system (Sage and White, 1984).

information processing modality - A channel of information transmission to the human operator. Wickens (1984) has written about modality selection from the Multiple Resource Theory perspective (i.e., visual vs. auditory channel information processing).

intent inferencing - The determination of a human operator's motive-driven behavior from the observation of overt control and monitoring actions (Geddes, 1989).

knowledge representation scheme - Any of a number of computer data structure representations of human knowledge to be embedded in an application. For example, scripts, plans, goals, and actions (Schank and Abelson, 1981) and coded representations of schemata are knowledge representation schemes.

learning acceleration - Increasing the familiarization and proficiency of the use of aided systems through concentrated interaction sessions with the aid. Can be specifically seen in embedded training systems, where training sessions can be run in times of low operator interaction requirements (Norcio and Stanley, 1989).

levels of autonomy (LOA) - From Krobusek et al. (1989). In the LOA methodology, automation is introduced according to discrete levels: 1) no intervention; 2) aid automatically executes tasks; 3) aid reminds pilot of

performed tasks; 4) aid prompts pilot about important tasks; 5) aid performs tasks when pre-specified conditions are met.

maintenance of user context - In the transformation mode of adaptive aiding, this procedure is used to sustain the user's perception of the same tasks and environment. Often, when a task is transformed to make it easier, the user may perceive two completely different tasks(i.e., original and transformed task). This may cause context switching problems and confusion for the user (Andes, 1990).

mathematically ideal decision maker - Theoretical decision maker that considers all relevant input signals regardless of time pressure, stress, or partial information content (Sen, 1984).

mixed dialogue initiative - A design principle of aiding system interfaces that attempts to reduce the cognitive load on the user by sharing the initiative for dialog. It is primarily goal-driven, template-based behavior that takes action as appropriate for user support or for eliciting behavior from the user. The system can also volunteer information when necessary. From Noah and Halpin (1986).

multiple alternative decision - From decision theory, this type of decision contains a number of alternative choices which are subjectively weighted by the decision maker's utility estimation functions (Keeney and Raiffa, 1976).

mission mode tailoring - An alternative approach to adaptive aiding in which the particular functions to be aided are identified by which mission segment, or "mode", that the system is currently engaged (e.g., ingress, attack, air escape, etc.) (Lind, 1989).

model-based communication - A component of implicit communication by which models of performance, intention, and/or task loading are relied on for expressing the current operator state to the aid. This approach can greatly reduce system overhead but suffers from greater ambiguity regarding the actions and intentions of each party (Revesman and Greenstein, 1986).

Modified Petri nets - A directed multigraph composed of nodes and arcs that are partitioned into two sets, places and transitions. Each arc is directed from an element in one set (place or transition) to an element of the other set. The nets were designed for modeling of systems with independent components (e.g., physical systems, social systems, computer hardware and software, etc.). They are used to model the occurrence of various events and activities in the system, particularly to model the flow of information or other resources in the system (Peterson, 1981).

navigational support - Often associated with hypertext interface systems, this type of user aiding assists the operator in the traversal of embedded information structure from within the system. Examples of navigational support include "return to top of stack" buttons, and graphical mapping of user traversal from within system.

operator tailoring - A process by which the system operator is allowed to customize the aiding interface and intervention threshold(s) according to personal preference (Andes, 1990).

progressive disclosure - An information presentation technique by which the system initially provides only summary information (i.e., maximum bandwidth of information), and will supply detailed information about the summary when queried by the operator (Noah and Halpin, 1986).

performance hysteresis - From Andes (1990). This phenomenon is a particular manifestation of the "hot potato" phenomenon. It is an impedance to smooth aid-operator interaction, where cyclic introduction and removal of aiding is observed based on changing operator performance. The operator's performance characteristics may exhibit local maxima, but the general performance trend is downward.

planning and commitment logic - One of the four general user-system tasks identified by Rouse and Rouse (1983). This logic is used by the operator in generating, evaluating, and selecting alternative courses of action within a control system.

procedural information - A primary type of aid status information. Refers to information pertaining to when to use the aid, or for determining intervention thresholds (Morris, Rouse, and Ward, 1985).

process information - A primary type of aid status information. Refers to functional information about the aid; information about the process by which the aid accomplishes its tasks. This information may allow the operator to determine the applicability of the aid to the current situation (Morris, Rouse, and Ward, 1985).

product information - A primary type of aid status information. Refers to information about normal aiding system output that allows the operator to determine whether the system is functioning properly (Morris, Rouse, and Ward, 1985).

proxy measures of primary indices of concern - Substitute measurements used in the determination of the need for aiding. These secondary indices (e.g., task percentage completion) can be used to estimate primary indices of operator performance when the primary quantity cannot be ascertained. Example is the use of operator intent inference in lieu of the operator explicitly indicating his intentions to the aid (Morris, Rouse, Ward, and Frey, 1984).

principles of adaptation - General design principles concerning when and how adaptive aiding applies, as well as the underlying mechanisms of adaptation (Rouse, 1988).

principles of interaction - General design principles that relate to the characteristics that foster (or hinder) operators' acceptance and utilization of adaptive aiding systems (Rouse, 1988).

random omission errors - An information processing strategy employed by operators under high information input parameters. The operator omits certain pieces of information on a random basis since he cannot consider all decision-affecting information at that high rate of input (Sen, 1984).

short-term memory support - The use of display technology to enhance the human's short- term memory store. For example, display of large lists of information should be maintained when the operator must refer to it often.

situation assessment - The process of interpreting relevant data from the environment in an effort to construct an accurate representation of the context based on current information needs (Andes and Small, 1992; conversation).

stimulus-response compatibility (displays and controls) - The relationship of the stimulus code to the response code (Barnes, 1981). Examples of S-R compatibility are normal population stereotypes (e.g, light switch up = on in the United States, off in England).

tailored logic - The employment of dynamic logic to adapt the system menus, command sets, and possible responses based on various environment triggers (e.g., mission mode, situation assessment). (Barnes, 1985).

task requirements centered - An archetypal aiding system design philosophy concerned primarily with the functional needs for which the system was designed.

task execution knowledge - Populated knowledge structures concerned with "how" a task is executed from within the system. This knowledge is specific to the execution of a task from within this particular system (not general); there can be several parallel instantiations of the task execution knowledge depending on the context in which the knowledge is activated (Andes, 1987).

task execution goal states - Knowledge representation schemes containing desired (or predicted) system states resulting from execution of a system task. Useful in determining the need for aiding, or for continued aid assistance (Andes, 1987).

timeliness of delivery - Refers to the optimal time window during which utility of the information to be displayed to the operator is at a peak. This is based on the operator's ability to interpret the information. Diminishing utility is associated with the age of the information (Andes, 1990).

user-initiated adaptation - An approach to adaptive aid invocation where the user explicitly requests assistance from the aid (Rouse, 1988).

vigilance support - Refers to a desired characteristic of the aid in which it monitors input streams for conditions satisfying predefined situations to which the user should be alerted in order to reduce the perceptual and cognitive load on the operator (Noah and Halpin, 1989).

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